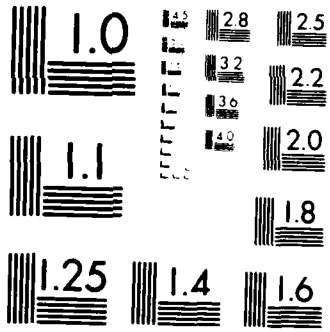
AD-A149 738 DIESEL FUEL ALTERNATIVES FOR ENGINES IN CIVIL WORKS 1/1
PRIME MOVERS(U) CONSTRUCTION ENGINEERING RESEARCH LAB
(ARMY) CHAMPAIGN IL B J SLIWINSKI ET AL. SEP 84
UNCLASSIFIED CERL-IR-E-200 F/G 21/4 NL



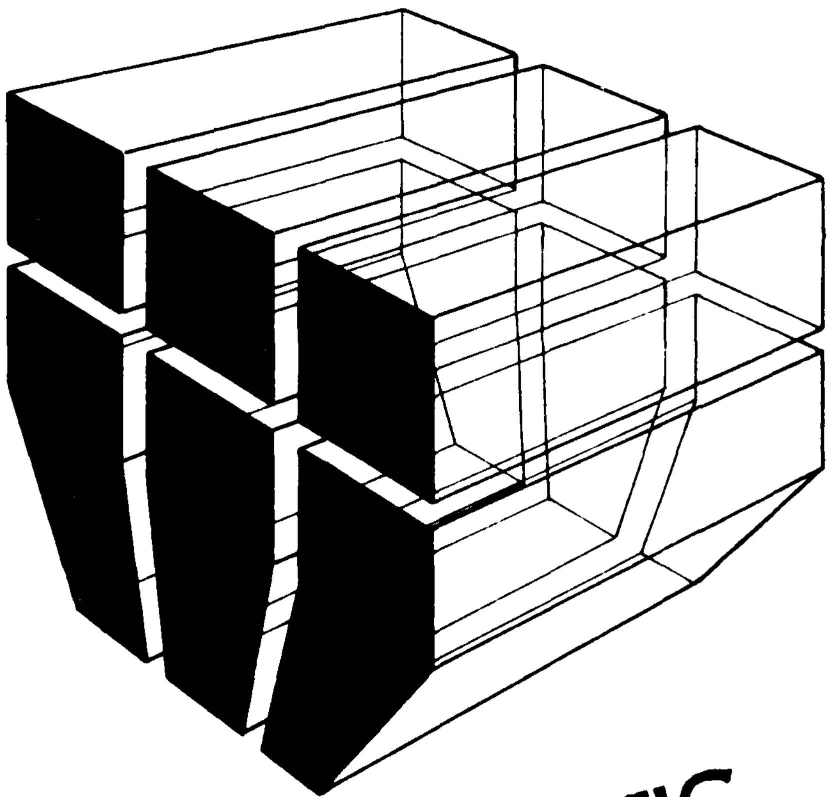
MICROCOPY RESOLUTION TEST CHART

US Army Corps
of Engineers
Construction Engineering
Research Laboratory

CERL

INTERIM REPORT E-200
September 1984
Technology to Reduce Petroleum Energy
Use in Civil Works

DIESEL FUEL ALTERNATIVES FOR ENGINES IN CIVIL WORKS PRIME MOVERS



by
B. J. Sliwinski
E. Corcoran

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CERL TR-E-200	2. GOVT ACCESSION NO.: AD A149 7_S
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Diesel Fuel Alternatives for Engines in Civil Works Prime Movers	5. TYPE OF REPORT & PERIOD COVERED: INTERIM
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): B. J. Sliwinski, E. Corcoran	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Construction Engr Research Laboratory, P.O. Box 4005, Champaign, IL 61820-1305	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: CWIS 33252
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE: September 1984
	13. NUMBER OF PAGES: 69
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Copies are obtainable from the National Technical Information Service
Springfield, VA 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

diesel fuels
fuel alternatives

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the first phase of research to determine fuel alternatives for Corps of Engineers medium-speed diesel engines. The literature has been searched to provide a background in current research and to identify the most promising alternatives to petroleum fuel. The criteria assessed were performance-based, with most variables compared to a No. 2 diesel fuel baseline.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

BLOCK 20. (Continued)

Results indicate that liquified coal, cetane-improved alcohol, and vegetable oils may be suitable alternatives. However, since much of the data reviewed were based on high-speed engines, additional data on medium-speed engines must be gathered before making final recommendations.

FOREWORD

This work was performed by the Energy Systems (ES) Division of the U.S. Army Construction Engineering Research Laboratory (USA-CERL) for the Directorate of Civil Works, Office of the Chief of Engineers (OCE), under Project 33252, "Civil Works Investigations and Studies"; Work Unit "Technology to Reduce Petroleum Energy Use in Civil Works."

Mr. Ben J. Sliwinski was the USA-CERL Principal Investigator and Mr. J. Bickley, DAEN-CWO-M, was the OCE Technical Monitor.

Mr. R. G. Donaghy is Chief of USA-CERL-ES. COL Paul J. Theuer is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

TABLES

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

DIESEL FUEL ALTERNATIVES FOR ENGINES
IN CIVIL WORKS PRIME MOVERS

1 INTRODUCTION

Background

U. S. Army Corps of Engineers Civil Works activities rely heavily on petroleum as an energy source. To minimize U.S. economic and political vulnerability associated with increased or continued dependence on foreign oil supplies, attention is being focused on fuel alternatives,[1] including alcohols, water/oil emulsions, coal, synfuels from shale and tar sands, vegetable oils, and several combinations of these. Such fuels would be used primarily for medium- to high-speed diesel engines that power Corps dredging, mat laying, and pumping.

Objective

The objective of this work is to identify diesel fuel alternatives to petroleum for powering civil works prime movers. The specific goal of this report was to evaluate selected alternatives based on a literature survey to identify those most suitable for continued study.

Approach

The literature was reviewed for the most current information on diesel fuel alternatives with respect to engine performance indicators such as thermal efficiency, knock, emissions, and wear.

Scope

Data in this evaluation are primarily from tests on high-speed diesel engines and are limited to a discussion of performance. Issues of fuel cost or availability are not addressed.

Mode of Technology Transfer

Upon completion of the final phases of this research, alternative fuel application characteristics and fuel system design guidance will be disseminated through an Engineer Technical Letter.

[1] Corps of Engineers Energy Program, Engineer Regulation 11-1-10 (Department of the Army, 15 April 1982).

2 ALCOHOLS

A fuel's ability to ignite quickly in a compression ignition (CI) engine is indicated by its cetane number (CN).* CN has been interpreted as describing the completeness of combustion obtainable, the extent of engine knock or failure, smoke emissions, and cold startability. In a range of 0 to 100, a typical diesel fuel has a cetane number of 53. Although this traditional rating system has been questioned for its applicability to unconventional diesel fuels,[2] this review will recognize its validity as well as the difficulties associated with it.

Alcohols have a CN of 0 to 15. Because of this poor ignition quality, they cannot be used as the sole fuel in CI engines but must be treated with cetane improvers, dual fueling, emulsification or blending with water or oils, increased ompression ratio (CR), increased inlet air temperature, or other techniques. The focus here is on the first three treatments.

In fuel modification with cetane improvers, nitrates are added to the alcohol and the resulting solution is substituted directly for the original fuel oil. Since cetane ratings are not directly correlated to ignition quality in fuel alternatives, Schaefer and Hardenberg[3] measured ignition quality as a function of ignition delay to determine blending ratios.* They defined the minimum improver requirement as the amount that would result in an ignition delay less than or equal to that of diesel fuel. Table 1 gives characteristics of various ignition improvers.[4] Although not explicitly stated in their report, it is assumed that equal ignition delays for the improved alcohols and diesel fuels resulted in similar levels of audible knock.

Improvers were evaluated in terms of safety, corrosivity, economy, and ease of manufacture (Table 2).[5] Since that investigation was conducted in Brazil, however, it may not be representative of the situation in the United States, especially in the area of manufacturing. Triethylene glycol dinitrate (TEGDN) and isoamyl nitrate are regarded as the most promising additives. Although kerobrisol BRA (a cyclohexyl nitrate) has an evaluation code equal to

---

*CN indicates the volume percentage of cetane (CN=100) in a blend of α-methylnaphthalene (CN=0).

[2] H. O. Hardenberg and E. R. Ehnert, "Ignition Quality Determination Problems with Alternate Fuels for Compression Ignition Engines," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: Society of Automotive Engineers [SAE], 1981), pp 51-57.

[3] A. J. Schaefer and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 (Warrendale, PA: SAE, 1981), pp 9-20.

*All tests were conducted on a single-cylinder DI engine with a bore of 97 mm (3.82 in.), a stroke of 128 mm (5.04 in.), and a CR of 17:1.

[4] A. J. Schaefer and H. O. Hardenberg, pp 13-14.

[5] A. J. Schaefer and H. O. Hardenberg, p 19.

Table 1

Characteristics of Ignition Improvers

Name	Main Components	MW* (g/mole)	Content** (% by wt)	Density*** at 20°C (kg/L)	Lower Heating Value (MJ/kg)	Minimum Admixture (% by vol)	Lower Heat Value of Fuel (MJ/L)	Lower Heat Value of Fuel (MJ/kg)	Energy Release per Equivalent Nitrate (MJ/equ.)	Oxygen+ Balance (%)
Kerobrisol MAR	Cyclohexyl nitrate	145.16	100	1.094	23.9	10	21.1	25.4	27.9	17.1
Cetanox 105	Isopropyl nitrate	105.09	100	1.036	17.2	25	19.9	23.1	8.1	31.6
DII3	Octyl nitrate	175.23	96	0.964	26.7	16	21.4	25.8	24.6	12.2
DII2	Prim. hexyl nitrates	147.18	98	0.983	24.6	12	21.0	25.5	26.2	16.2
Ethyl nitrate		91.07	100	1.108	13.7	>>20				46.2
Butyl nitrate		119.12	99	1.026	20.6	20	20.7	24.4	12.0	24.0
Isoamyl nitrate	Isomeric pentyl nitrates	133.15	98	0.996	22.6	16	20.9	25.0	17.4	19.4
2-Ethoxyethyl nitrate		135.12	100	1.118	17.2	10	20.4	24.5	24.6	32.0
DEGDN		196.12	100	1.385	10.8	5	20.3	24.4	28.9	58.3
DEGDN desensitized	DEGDN; castor oil; ethylene glycol	196.12	64	1.24	15.9	7.8++	20.5	24.4		34.1
TEGDN		240.17	100	1.338	13.2	4	20.5	24.8	46.5	44.4
Kerobrisol BRA	Triethyl ammonium	164.21	85	1.077	20.8	16	20.9	24.6	23.3	15.0

Source: A. J. Schaefer and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 (Warrendale, PA: Society of Automotive Engineers, 1981), pp 13-14.

*Molecular weight of main component only.
**Content of main component in final product.
***Related to final product
+Oxygen balance of main component; related to the final product only in the case of DEGDN desensitized.
++Calculated on the basis of a minimum admixture of DEGDN of 5 percent by volume.

For ethanol, the following values apply:
a) Pure ethanol
Density (20°C): 0.7893 kg/L
Lower heat value: 26.8 MJ/kg (21.1 MJ/L)
b) Azeotrope (4.4% by weight water)
Density (20°C): 0.804 kg/L
Lower heat value: 25.6 MK/kg (20.6 MJ/L)

Table 2

Ignition Improvers Evaluation

Name	Manufacturability	Safety	Corrosiveness	Economy	Evaluation* Code
Kerobrisol MAR	--	+	o	-	n.a.
Cetanox-105	-	+	o	-	-1
DII3	--	+	o	-	n.a.
DII2	--	+	o	-	n.a.
Ethyl nitrate	++	--	o	-	n.a.
Butyl nitrate	o	+	o	o	+1
Isoamyl nitrate	+	+	o	++	+4
2-Ethoxyethyl nitrate	++	+	o	o	+3
DECDN	++	--	o	++	n.a.
DECDN desensitized	++	o	o	o	+2
TECDN	++	o	o	o	+4
Kerobrisol BRA	++	+	-(--)	(++)	+4 (n.a.)

Source: A. J. Schaefer and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 (Warrendale, PA: SAE, 1981), p 19.

*Sum of all evaluation criteria; an evaluation "--" results in the comment "n.a." (not applicable).
++ very good
+ good
o without effect or not ascertainable
- poor
-- very poor, cannot be used

the two just mentioned, its very poor corrosive tendencies prohibit its consideration.

Ethanol/DII2 (DII2 is a mixture of primary hexylnitrates) was investigated to test the performance of cetane-improved alcohols in diesel engines.[6] For these experiments, the fuel injection quantity was adjusted to compensate for the lower heating value of alcohol, and the injection nozzle holes were modified to accommodate a larger fuel flow. Tests showed that diesel and ethanol fuels had very similar performance in terms of brake mean effective pressure (BMEP) and brake specific fuel consumption (BSFC) (Figure 1).[7] BMEP

[6]A. J. Schaefer and H. O. Hardenberg, p 14.
[7]A. J. Schaefer and H. O. Hardenberg, p 14.

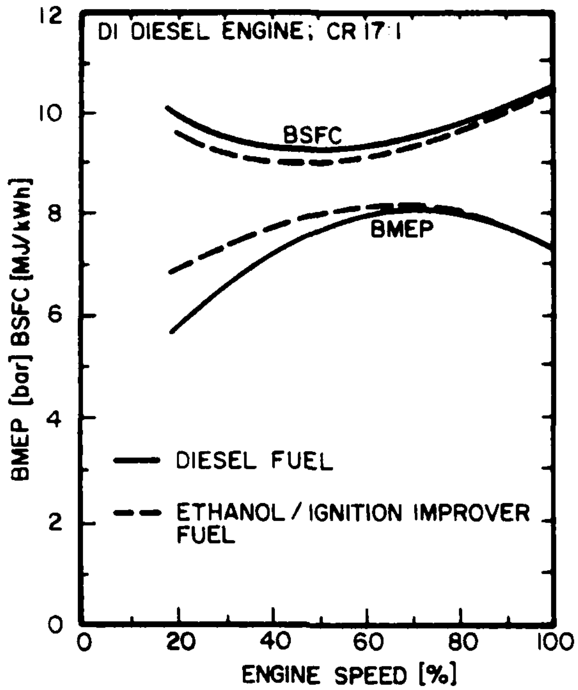


Figure 1. Full-load BMEP and BSFC versus engine speed for diesel and ethanol/ignition improver fuel. (Source: A. J. Schaefer and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 14.)

is the average pressure on the piston during the power stroke and is derived from measuring the brake horsepower output. BSFC is proportional to the inverse of the overall thermal efficiency and is indicative of the fuel consumption rate (energy input) per rate of energy output.

Emissions from engines with the improved ethanol showed fewer hydrocarbons and nitrous oxides and less black smoke than the diesel-fueled engine under most operating conditions (Figure 2).[8] Oxides of nitrogen were greater than diesel emissions, while engine speed was below 45 percent capacity, but less than the diesel at faster speeds. This result is contrary to expectations, since the alcohols were improved with nitrates. However, unburned ethanol and aldehydes in the exhaust were not measured.

Alcohol fumigation involves the addition of alcohol to an engine's intake air. In addition, diesel fuel is injected in the normal way to act as a pilot light for the alcohol. Heisey and Lestz[9] experimented with the alcohol fumigation in a diesel engine with simultaneous diesel fuel injection to monitor effects on thermal efficiency, combustion, smoothness, and emissions.

The experimental engine was a four-cylinder, 4.47-kW (6-Bhp) diesel with a 76.2-mm (3-in.) bore, 77.79-mm (3.0625-in.) stroke, 21.7 CID, 18:1 CR, and a

[8] A. J. Schaefer and H. O. Hardenberg, p 15.

[9] J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Tulsa, OK: SAE, 1981), pp 1-14.

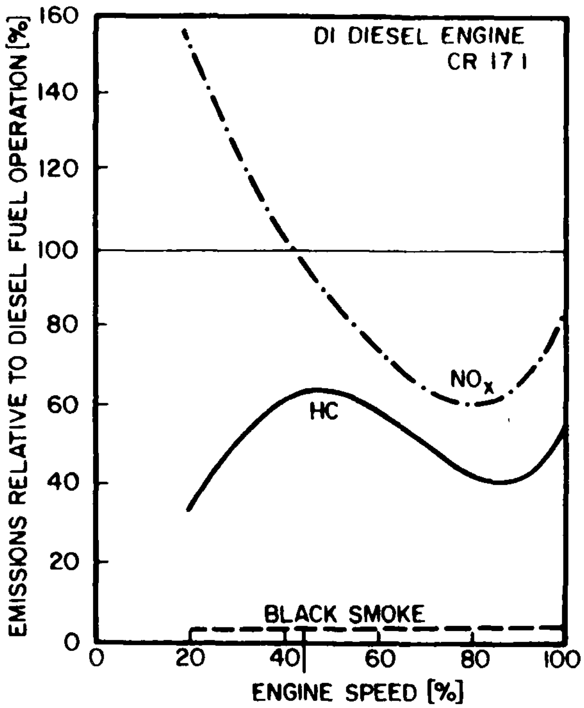


Figure 2. Relative exhaust emissions at full-load operation with ethanol/ignition improver fuel. (Source: A. J. Schaefer and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 15.)

rated speed of 3000 rpm. With this engine, up to 30 percent of the energy requirement could be substituted with ethanol, with the amount of substitution limited by ignition failure or knock. The amount substituted could be increased, however, as the load setting was increased. The brake thermal efficiency (BTE) of various combinations of ethanol and water was plotted as a function of fumigated ethanol at 2400 rpm (Figure 3).[10] All fuels were tested to their misfire limit.

At large load settings, BTE rose somewhat with increased percentages of alcohol. This increased efficiency is assumed to be due to rapid combustion near top dead center, which approximates a constant-volume process. This nearly constant-volume combustion is closer to an Otto cycle than a diesel cycle and is more efficient for the fixed-compression ratio of the engine hardware. Rapid combustion is promoted by the increased ignition delays and, therefore, the large quantities of vaporized alcohol present at ignition. Pressure rise is greater for this combustion and may be due to the more rapid release of heat and the larger quantity of moles of product formed during alcohol combustion. Also, heat loss may be reduced in this rapid combustion.

At smaller load settings, for example, at 1/3 load, BTE is lower, and less alcohol substitution is permitted before misfire. At this load, less

[10] J. B. Heisey and S. S. Lestz, p 5.

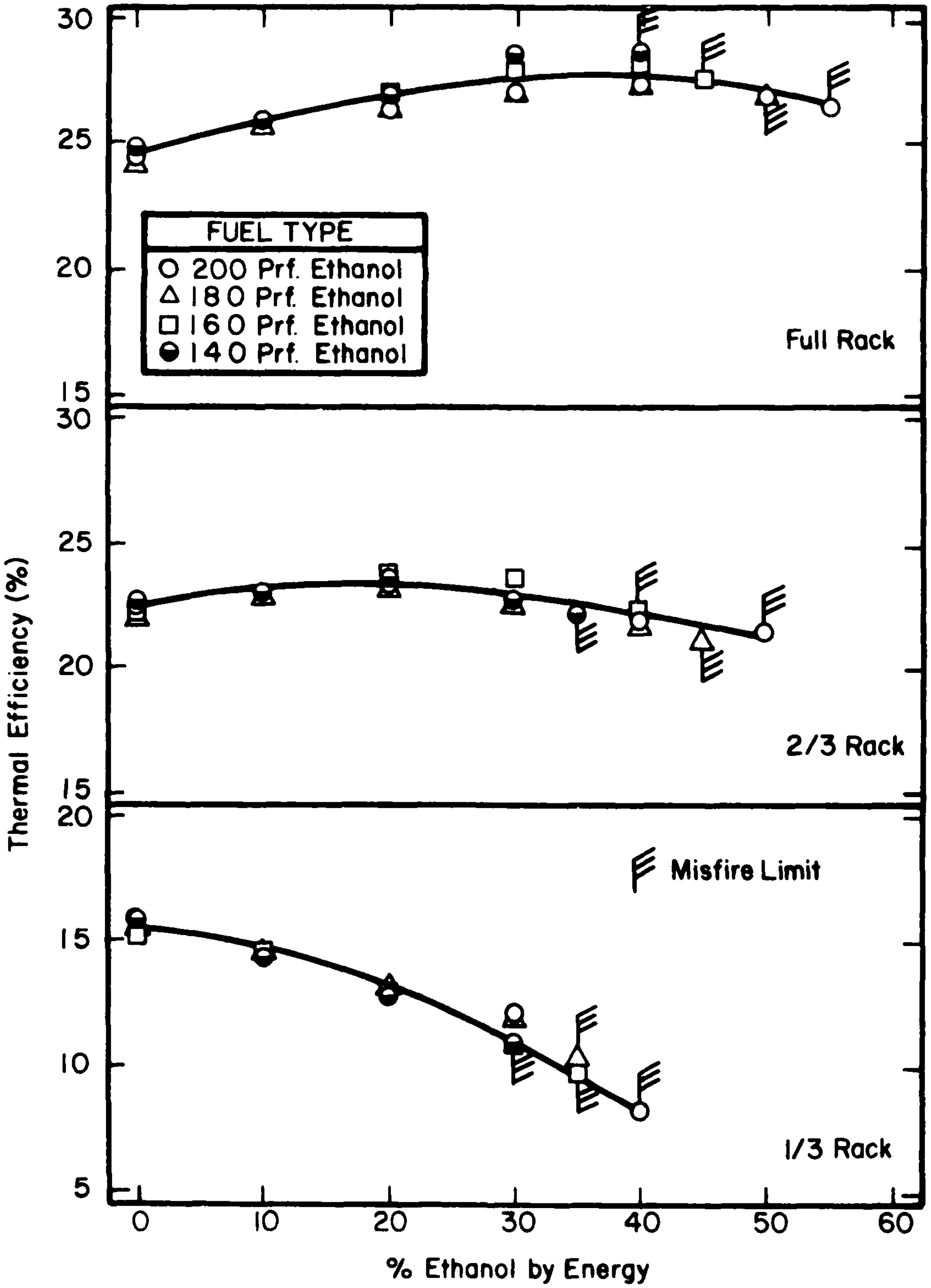


Figure 3. Thermal efficiency as a function of fumigated ethanol at 2400 rpm. (Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 [Tulsa, OK: SAE, 1981], p 5.)

total heat is released and a proportionately larger amount of this heat is lost. Furthermore, less net heat is available for combustion, and burning quality deteriorates.

The amount of water in the fuel had minimal effects on engine performance, although the increased water percentage in the lower proof fuels did expedite combustion quenching. Duplicate tests with methanol showed similar results at medium and high loads, but slightly decreased performance at low loads.

Ignition delay lengthened with greater additions of alcohol (Figure 4),[11] as well as with decreasing alcohol quality (i.e., lower proof). This increased delay led to combustion knocking. Figure 5 shows the region of intense knock.[12] In this interval, combustion noise increased due to lengthy ignition delay, which resulted in cooling of the vaporizing alcohol; rapid combustion of large amounts of vaporized alcohol at ignition also contributed to the noise.

Emissions of nitrous oxides, carbon monoxide, and particulates were monitored in this fumigation experiment. Figures 6 and 7 show the nitrous oxides and carbon monoxide emissions as a function of fumigated ethanol.[13] In general, nitrous oxides emission increased over baseline conditions at full load, remained fairly stable at 2/3 load, and decreased at light load. These emissions were dependent on water, such that greater water concentrations led to fewer emissions. Carbon monoxide emissions increased with additional alcohol substitution at 1/3 and 2/3 load, but had little change at full load. Since the amount of carbon monoxide emissions indicates completeness of combustion, the high latent heats of vaporization for the alcohol may have required more heat than could be supplied at lower load settings.

Table 3 gives particulate emissions for this fumigation experiment.[14] These data show a general decrease in particulate emissions with increasing alcohol fumigation.

Two concerns not thoroughly analyzed but mentioned in the Heisey and Lestz report are particulate biological activity and engine wear. Limited testing showed increased biological activity of particulates, with potential impact on public health not mentioned. Brief visual and physical measurements of engine components showed no abnormal wear of the combustion chamber and piston.

Shirvani evaluated various mixtures of alcohol and diesel fuel using alcohol blends of No. 4 diesel oil (D4) and heavy virgin distillate (HVD)

---

[11] J. B. Heisey and S. S. Lestz, p 6.
[12] J. B. Heisey and S. S. Lestz, p 7.
[13] J. B. Heisey and S. S. Lestz, pp 7-8.
[14] J. B. Heisey and S. S. Lestz, p 9.

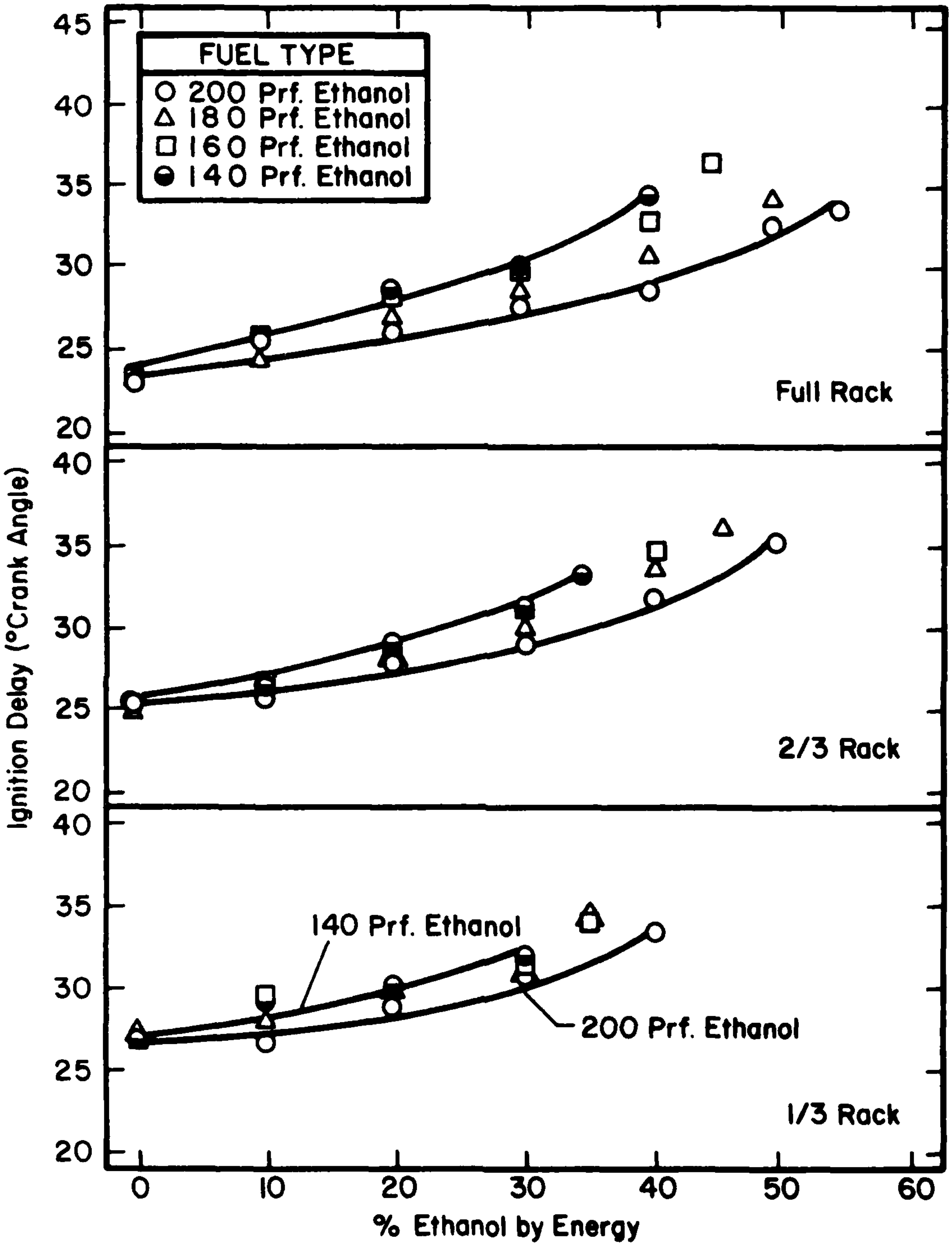


Figure 4. Ignition delay as a function of fumigated ethanol at 2400 rpm. (Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 [Tulsa, OK: SAE, 1981], p 6.)

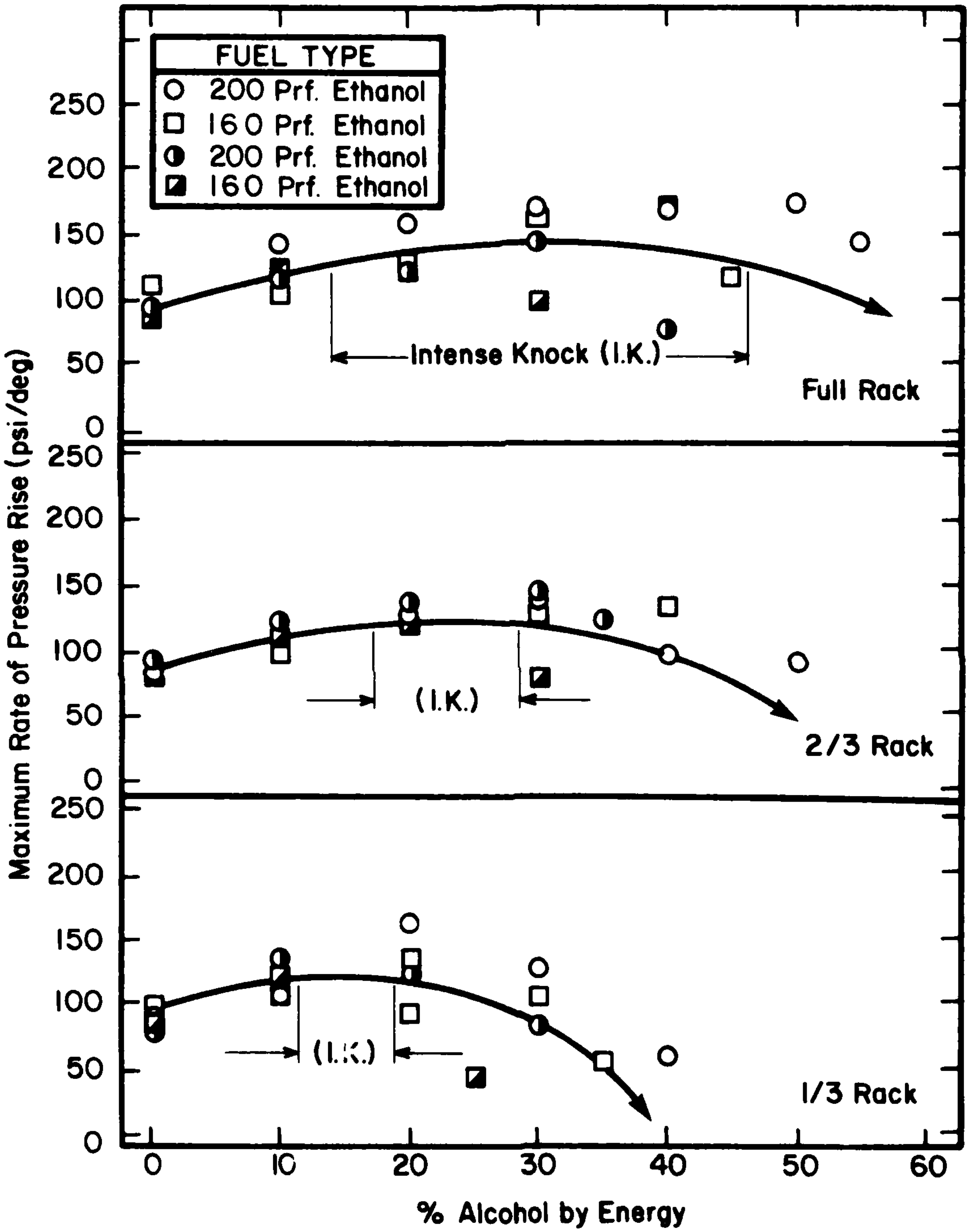


Figure 5. Comparison of rate of pressure rise for ethanol and methanol fumigants at 2400 rpm. (Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 [Tulsa, OK: SAE, 1981] p 7.)

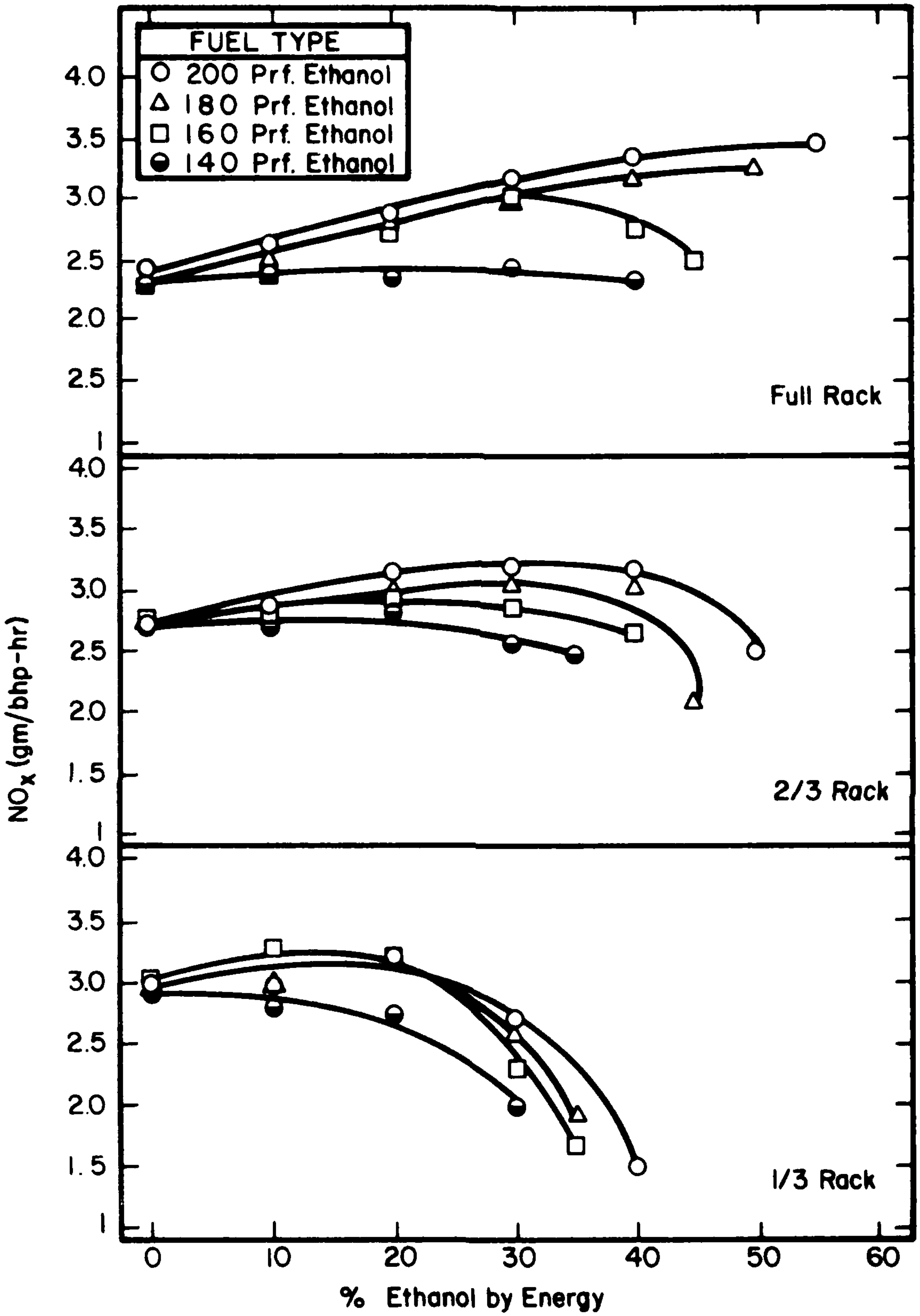


Figure 6. Nitrous oxides emission as a function of fumigated ethanol at 2400 rpm. (Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 [Tulsa, OK: SAE, 1981], p 7.)

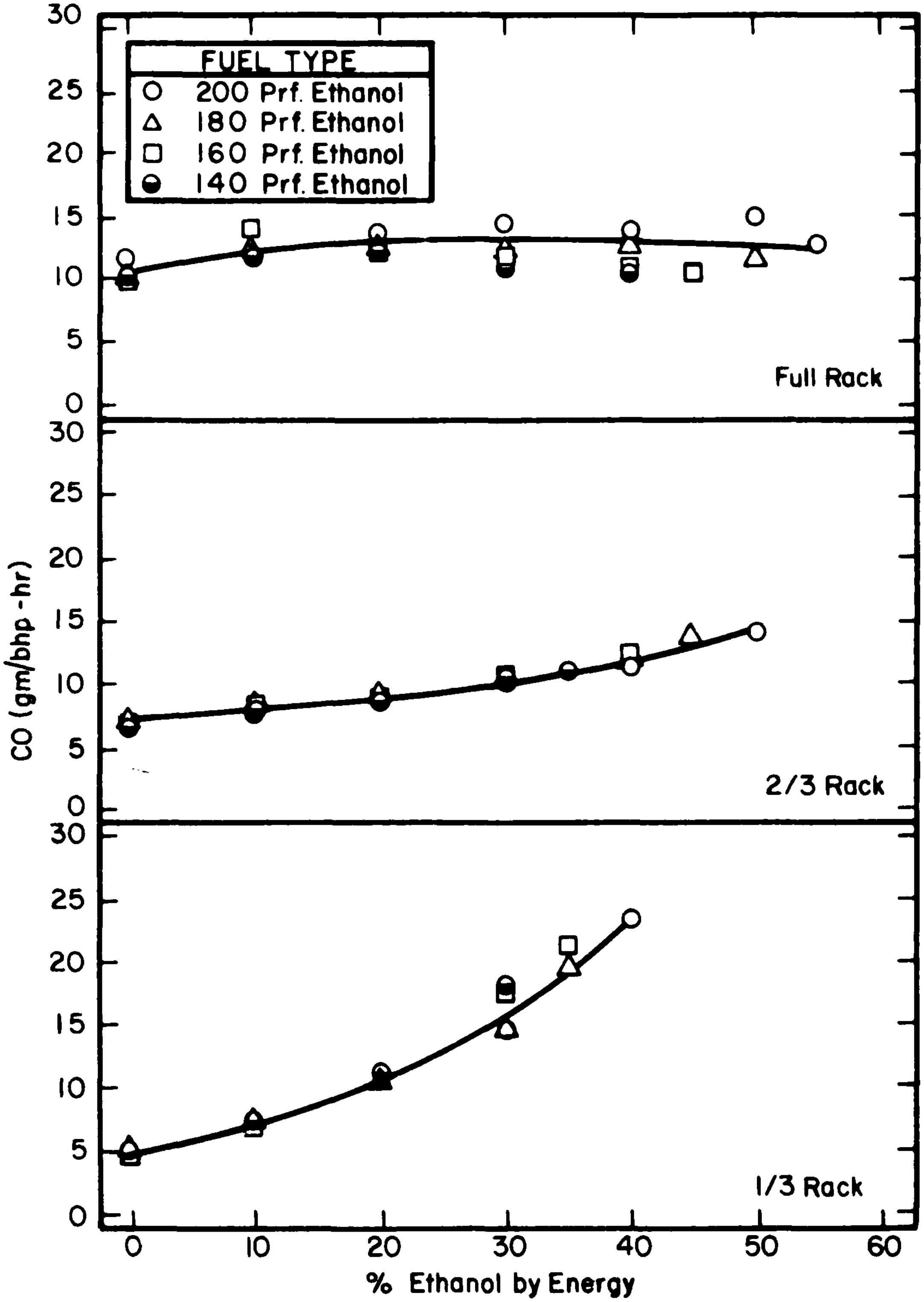


Figure 7. Carbon monoxide emission as a function of fumigated ethanol at 2400 rpm. (Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 [Tulsa, OK: SAE, 1981], p 8.)

Table 3

Summary of Particulate Data

Fuel	RACK 1/3		2/3			Full		
200-Proof Ethanol	22027. 0. 3.06 41.[illegible] 1.12 8.9 ± .5	22027. 20. 2.68 61.9 - 4.6 ± .4	32643. 0. 7.21 20.0 .37 6.7 ± .7	32643. 20. 4.97 33.6 1.6 19.8 ± 3.5	32643. 40. 2.0 57.0 - 6.9 ± 1.1	43317. 0. 14.62 9.9 .11 5.5 ± 1.0	43317. 20. 10.18 7.3 .17 18.1	43317. 40. 5.14 23.1 .77 18.7 ± 4.5
180-Proof Ethanol				32643. 20. 5.07 28.1 - 21.7 ± 3.6				
160-Proof Ethanol				32643. 20. 5.69 53.9 - 10.1 ± 1.25				
140-Proof Ethanol				32643. 20. 5.38 43.1 - 6.9				

Source: J. B. Heisey and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Tulsa, OK: SAE, 1981), p [illegible].

Data in each block are tabulated as follows:
- Total fuel energy input rate - Btu/hr
- Percent of total fuel energy input as ethanol
- Particulate deposition rate - mg/min
- [illegible]
- [illegible] results, TA38, mean of slope ± st dev [illegible]
  - [illegible]
  - [illegible]

similar to SAE No. 2 diesel fuel specifications. The viscous distillates were added in an attempt to upgrade the alcohol fuel. Table 4 gives the composition of experimental blends,[15] and Table 5 lists properties of the blends and their components.[16] These compositions were derived empirically to eliminate mixing and cetane problems while staying within SAE specifications.

Tables 6 and 7 show requirements for diesel fuel oil as suggested by SAE and the American Society for Testing and Materials (ASTM)[17] based on viscosity, heating value, mineral content, and pour point. Fuel viscosity indicates resistance to flow, which affects the engine's injection system by resisting division into a spray. Low-viscosity fuels promote lubrication problems and may cause wear. High-viscosity fuels can cause major pump resistance and damage to the filter. Heating value is the fuel flow rate required to produce the desired output and is indicative of the energy potentially available for combustion. Sulfur, ash, water, and sediment contents are minimized to avoid deposits that could abrade engine parts, accelerate corrosion, and block injector systems. Pour point is the lowest fuel temperature at which pumping can continue. This value can be crucial in cold climates. Synthesis of appropriate blends must take these fuel properties into consideration.

All tests were run at very high speed (1754 to 2193 rpm) on a four-cylinder, four-stroke, DI diesel with a 96.8-mm (3.81-in.) bore, 104.8-mm (4.13-in.) stroke, 16.5:1 CR, and rated at 31 kW (Bhp 41.57). All blends for this

Table 4

Volume Composition of Blended Fuels (Volume %)

Fuel	D2	D4	HVD	Ethanol	Butanol	Cetane Improver
HVD blend	0.0	0.0	75	15	10	0.0
D4 blend w/CI	48.5	4.85	0.0	29.1	14.6	3.0
D4 blend w/o CI	50	5.0	0.0	30	15	0.0

Source: H. Shirvani, et al., Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 (SAE, 1981).

[15] H. Shirvani, Alternate Fuels for Diesel Engines, unpublished master's thesis (University of Illinois, 1982), p 25.

[16] H. Shirvani, C. E. Goering, and S. C. Sorenson, Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 (Warrendale, PA: SAE, 1981).

[17] H. Shirvani, et al.; C. E. Goering, et al., "Fuel Properties of Eleven Vegetable Oils," Transactions of the American Society of Agricultural Engineers (ASAE), Vol 25, No. 6 (1982), p 1473.

Table 5

Fuel Properties

Fuel	Viscosity (mm^2/s)	Specific Gravity	LHV (kJ/kg)	Cetane No.	Sulfur (%)	C/H Mass Ratio	Stoichiometric A-F Ratio
Ethanol (C_2H_5OH)	1.17	0.789	26.90*	15**	0.0	4.00	9.00
Butanol (C_4H_9OH)	2.33	0.810	33.22*	--	0.0	4.80	12.06
Diesel No. 2 ($C_{16}H_{28.8}$)	2.15	0.840	42.59***	46.6+	0.22***	6.67***	14.52
Diesel No. 4 ($C_{16}H_{25.3}$)	--	0.913	41.46***	--	0.98***	7.59***	14.10
HVD ($C_{16}H_{29.45}$)	4.47	0.852	45.52***	--	0.39***	6.52***	14.48
Primary Alkyl Nitrate ($C_8N_1O_3H_{17}$)	--	0.964	29.77	--	0.0	5.65	9.61
Diesel No. 4 Blend (w/Cetane Improver)	2.00	0.830	36.40	40.8+	0.160	5.66	12.19
Diesel No. 4 Blend (w/o Cetane Improver)	2.04	0.830	36.66	25+	0.167	6.36	12.35
HVD Blend	3.00	0.840	39.42	38+	0.297	6.00	13.49

Source: H. Shirvani, et al., Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 (SAE, 1981).

*E. F. Obert, The Internal Combustion Engine and Air Pollution, 3rd ed. (Harper and Row, 1973).
**N. P. Cheremisinoff, Gasohol for Energy Production (Ann Arbor Science, 1979).
***C. A. Krawetz, Test Report No. 01215 2-4 from Phoenix Chemical Lab., Inc., Chicago, IL (1980).
+W. B. Gross, Cetane Rating Log Sheets from Workshop Engine Div. of Dressler Industries, Waukesha, WI (1980).

Table 6

Detailed Requirements for Diesel Fuel Oils

Diesel Fuel	Flash Point (°C)	Water and Sediment (vol %)	Ash Weight (%)	Distillation Temperatures at 90% Point (°C)		Kinematic Viscosity (mm^2/s)		Sulfur Weight (%)	Cetane No.
	Min	Max	Max	Min	Max	Min	Max	Max	Min
No. 1	38	0.05	0.01	--	288	1.3	2.4	0.50	40
No. 2	52	0.05	0.01	282	388	1.9	4.1	0.5	40
No. 4		0.50	0.10	--	--	5.5	24.0	2.0	30

Source: H. Shirvani, Alternate Fuels for Diesel Engines, unpublished master's thesis (University of Illinois, 1982).

Table 7

Tests and Limits for No. 2 Diesel Fuel Properties

Test	ASTM Test No.	ASTM Limits
Viscosity (mm^2/s)	D445	1.9-4.1
Distillation temperature (°C)	D86	282-338 @ 90% pt.
Cloud point (°C)	D2500	*
Pour point (°C)	D97	**
Flash point (°C)	D93	52 min.
Water and sediment (% by vol)	D1796	0.05% max.
Carbon residue @ 10% residium	D524	0.35% max.
Ash by weight (%)	D482	0.01% max.
Sulfur by weight (%)	D129	0.5% max.
Sulfur, copper corrosion	D130	***
Cetane no.	D613	40 min.

Source: C. E. Goering, et al., "Fuel Properties of Eleven Vegetable Oils," Transactions of the American Society of Agricultural Engineers (ASAE), Vol 25, No. 6 (1982), p 1473.

*Cloud point is not specified by ASTM. Satisfactory operation should be achieved in most cases if the cloud point is 6°C above the tenth percentile minimum temperature for the area where the fuel will be used.

**Pour point is not specified by ASTM, but generally occurs at 4.4 to 5.5°C below the cloud point (Liljedahl, et al., 1979).

***This test for active sulfur is interpreted by comparison of the immersed strip with standard immersed strips. Corrosion shall not exceed that on a No. 3 standard strip.

engine were premixed and injected with the existing fuel injection system, since the engine was not modified. Various engine performance indicators were plotted against the equivalence ratio (ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio) to compensate for the difference in stoichiometric fuel/air ratios.

Addition of ethanol to No. 2 diesel fuel degrades the fuel by lowering its heat content, viscosity, CN, and stability. Lower heat content reduces power output and increases fuel consumption per unit of work. Figures 8 and 9 show trends in Bhp (see BMEP data) and BSFC.[18] Highest performance was obtained from the blends at 2000 rpm. At the lower speeds (1754 rpm), BMEP and, thus, power output were less than those for the baseline fuel; at mid- and high-range, BMEP and power were equal or slightly higher than the baseline fuel's. Also, power output for all fuels increased with a richer fuel mixture (high equivalence ratio). BMEP was directly proportional to power output in these tests because the speed was held constant.

Although data at varying speeds are not shown, the increase in BSFC was more pronounced at lower speeds. Phase separation was a stability problem with the ethanol and diesel fuel mixture attributed to water contamination or structural differences between alcohols and hydrocarbons.

The ethanol blend's lower CN delayed combustion and increased noise. Knocking in a CI engine results from a high rise in combustion chamber pressure. If ignition is delayed too long and the fuel's self-ignition temperature is too high, a comparatively large amount of fuel will be in the cylinder. This heavy fuel concentration can raise the pressure rapidly enough to cause a pressure wave propagation and, thus, knock. Longer ignition delay was detected in the fuel blends compared to baseline fuels, but this condition improved as the equivalence ratio increased.

Thermal efficiency of the ethanol-diesel blend is lower than that of neat (undiluted) diesel fuel at medium and light loads, but is mostly consistent with the diesel efficiency at full load. More complete combustion at high loads is assumed to produce this better efficiency. Experimental results confirmed that BTE closely paralleled the baseline fuel at high speeds; at lower speeds (1745 rpm), the BTE diminished no more than 10 percent.

Positive aspects of burning ethanol diesel blends instead of No. 2 diesel fuel include (1) less smoke and (2) lower exhaust temperature resulting from ethanol's higher heat of vaporization and, thus, the greater energy requirement to vaporize the blend. This larger energy consumption leaves less energy in the exhaust and, hence, a lower exhaust temperature.

---

[18] H. Shirvani, et al.

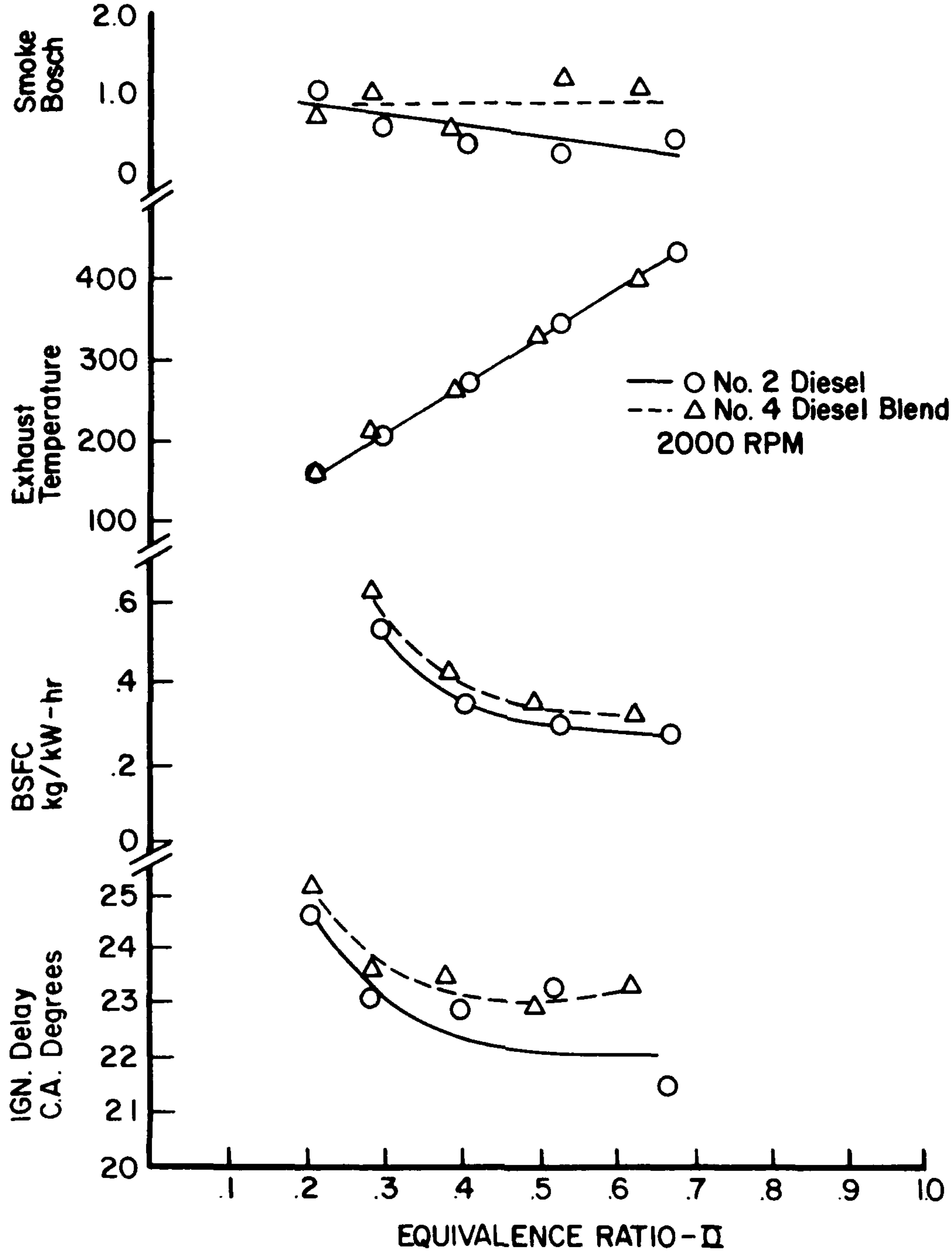


Figure 8. Performance of D4 blend and D2 at 2000 rpm. (Source: H. Shirvani, et al., Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 [Warrendale, PA: SAE, 1981]).

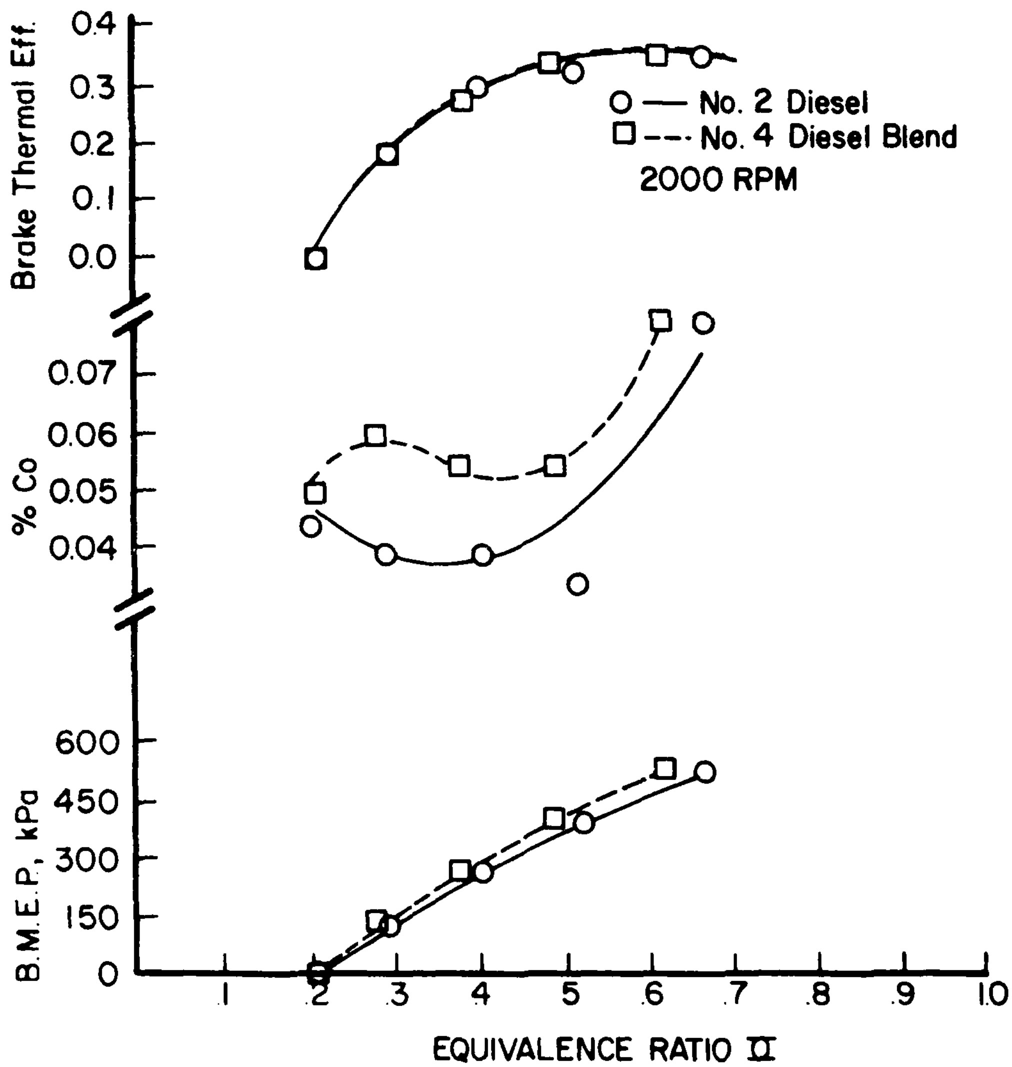


Figure 8 (cont'd).

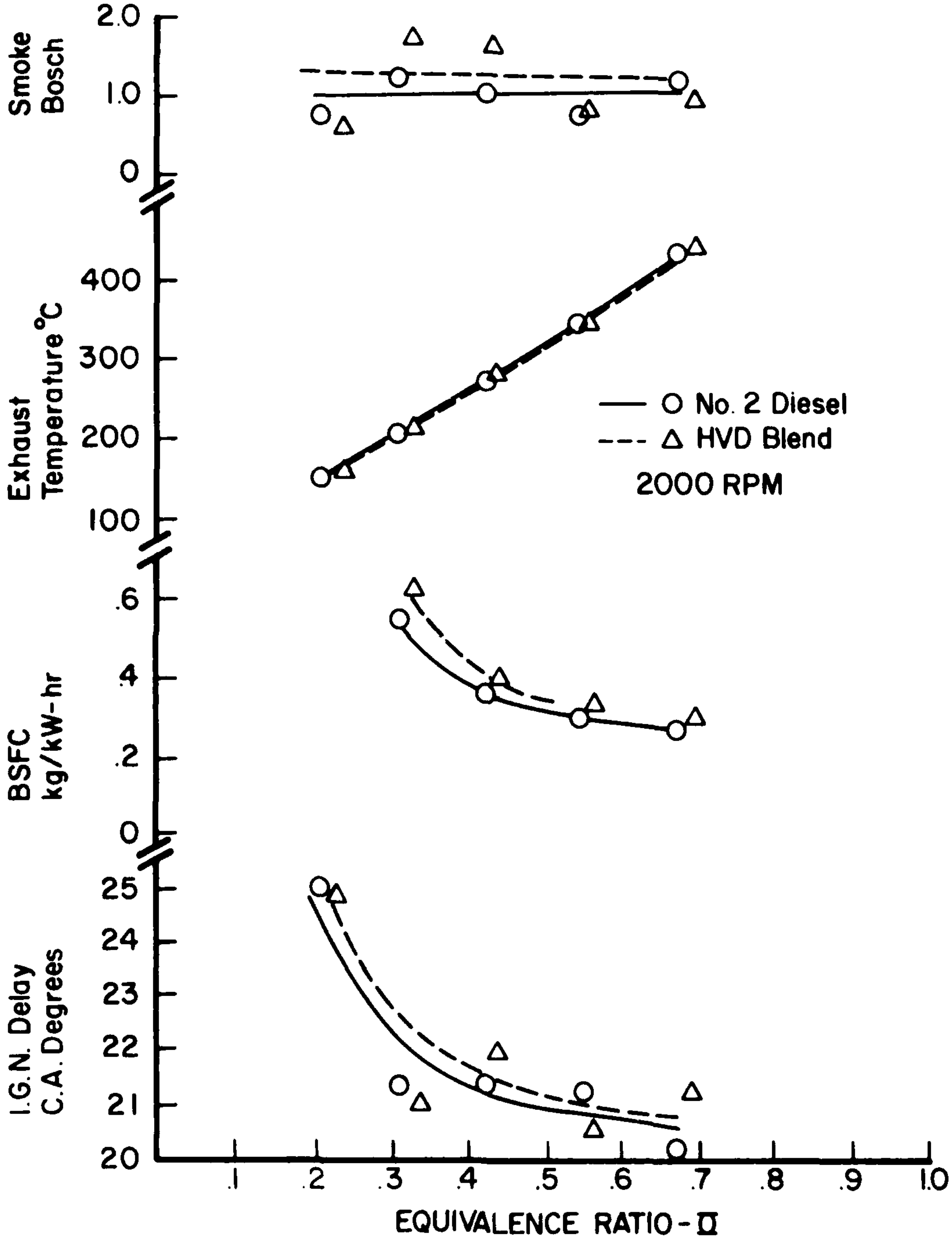


Figure 9. Performance of HVD blend and D2 at 2000 rpm. (Source: H. Shirvani, et al., Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 [Warrendale, PA: SAE, 1981]).

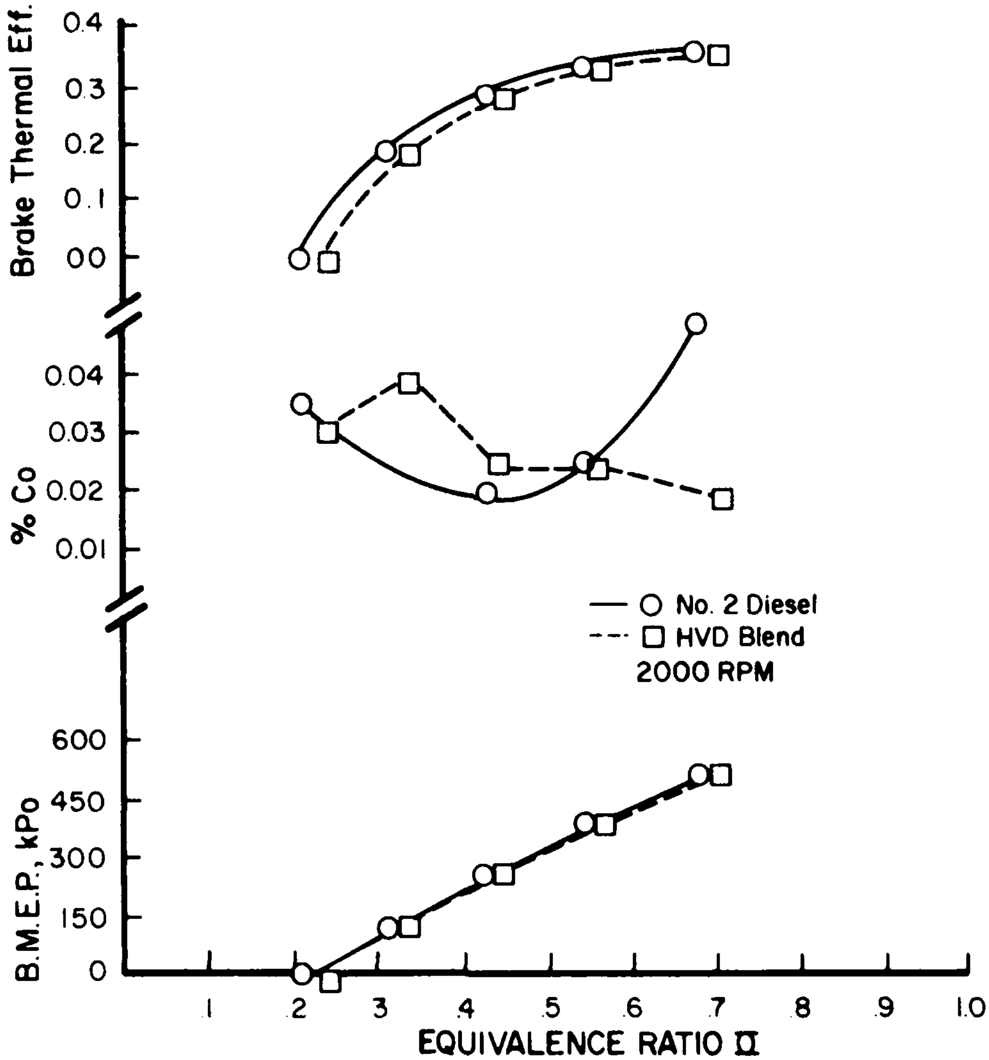


Figure 9 (cont'd).

Figure 10 shows the petroleum savings with blended els[19] expected results if the mixtures were burned with a thermal efficiency equal to the baseline fuel. These results show that the D4 blend can produce a 20 to 37 percent petroleum savings and the HVD blend can produce up to 18 percent savings. The savings depend on engine load and speed.

Butanol-diesel blends are promising alternatives. Miller and Smith[20] found little effect on Bhp with diesel-butanol blends. Butanol can also be mixed in most concentrations without phase separation.

To summarize these data, alcohol fuels tended to require high speeds and high loads for satisfactory performance. Thermal efficiency reached or exceeded diesel results at very high speeds (above 1500 rpm) and medium or heavy loads (2/3 and full loads, respectively) in blending and fumigation tests. At low loads, fumigation techniques could not meet baseline diesel fuel efficiency, nor could alcohol-oil blends at speeds relatively low for the testing range (1754 rpm). Similar BSFC data between cetane-improved alcohol and diesel fuel indicated comparable efficiencies for the two fuels. Speed information to accompany efficiency data was not included in Schaefer and Hardenberg's report on improved alcohol.

Horsepower ratings for alcohol fueling techniques were included only in Shirvani's findings on alcohol blends. These blends increased hp at high speed, produced no change at medium speed, and decreased output at low speed. Although Shirvani categorized these test speeds into high, medium, and low, that entire test range is classified as very high-speed in this report. Results on hp output were not included for cetane-improved alcohol testing, but BMEP data were. BMEP for improved alcohols parallel diesel fuel values and suggested a parallel in Bhp as well.

Knock apparently was no problem in the cetane-improved alcohol fuels. Audible knock was detected during fumigation and blend trials, but was not quantified. Descriptive observations mentioned increased knock with increased alcohol fumigation and with decreased equivalence ratio in alcohol-diesel oil blend runs.

Emission information was recorded to varying degrees for the three technologies. With cetane-improved alcohol and alcohol-oil blends, less black smoke was emitted than with baseline diesel fuels. However, black smoke levels were not monitored during fumigation. Nitrous oxides emission was greater with cetane-improved alcohols than for diesel fuel at less than 45 percent of some unknown speed capacity, but was less than diesel at higher speeds. The nitrous oxide emissions during very-high-speed testing with fumigation revealed fluctuation with load: quantities were higher than for diesel

---

[19] H. Shirvani, et al.

[20] C. L. Miller and J. L. Smith, "Using Butanol Fuel Blends," ASAE Paper 80-15 24, presented at ASAE Winter Meeting, 2-5 December 1980 (St. Joseph, MI: ASAE, 1980).

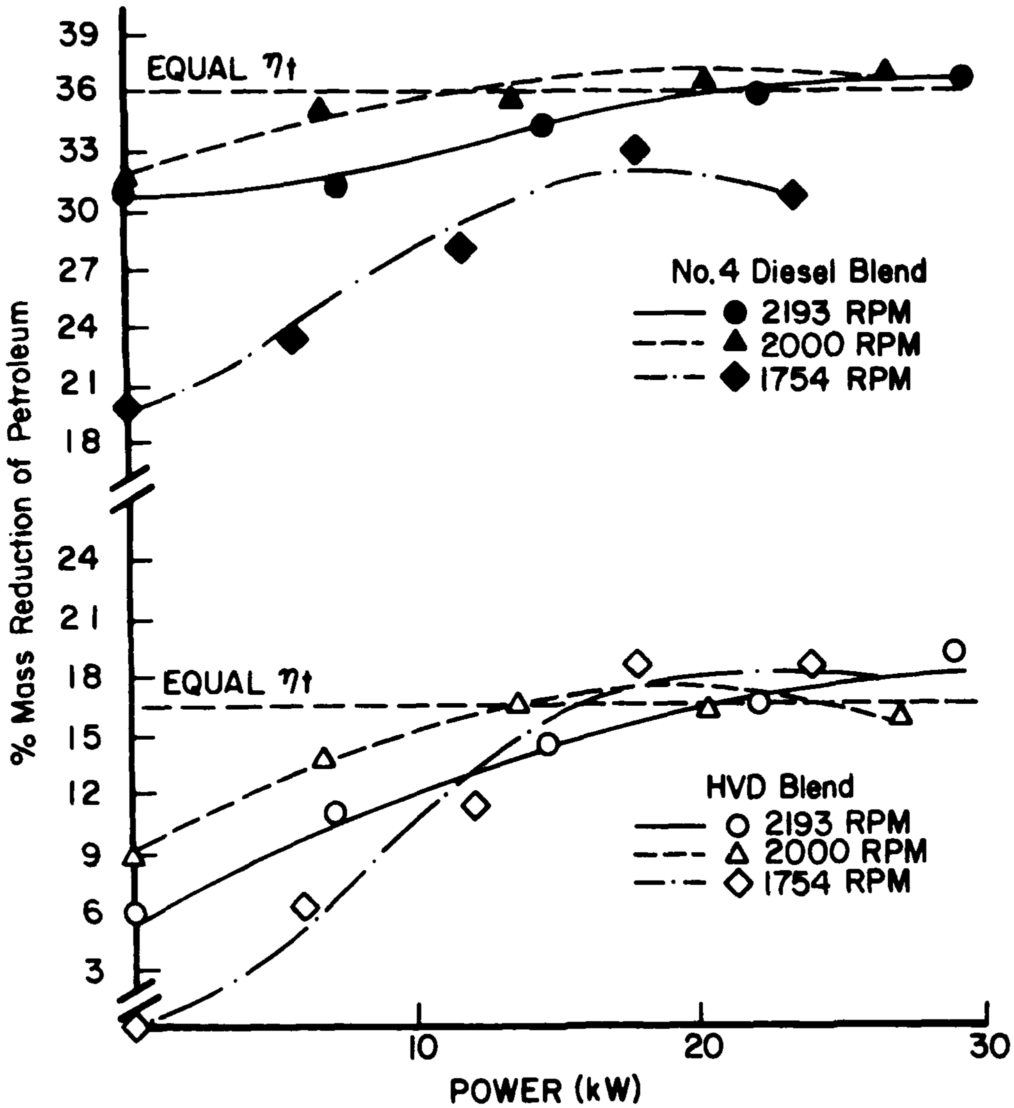


Figure 10. Petroleum savings with blended fuels. (Source: H. Shirvani, et al., Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 [Warrendale, PA: SAE, 1981].

exhaust at full load, mostly consistent at 2/3 load, and lower at 1/3 load. Improved-alcohol exhaust had lower hydrocarbon concentrations and alcohol-oil blends had lower temperatures. Carbon monoxide emissions during fumigation were higher at light and medium loads, but not increased significantly over baseline diesel fuel emissions at full load. Table 8 summarizes experimental results with the alcohol fuels.*

*Table 8 also summarizes test results from water-oil emulsion fuels. However, since these experiments show no significant fuel savings or emission improvement, no further space is devoted to this discussion.

Table 8

Summary of Experimental Results

Fuel	Combustion technology	Retrofit requirements	Test engine specifications	BTE or related factors	Power output or related factors	Knock	Emissions	Engine wear	Other
Alcohol w/cetane improvers (ethanol/DII-2)	Direct substitution for diesel fuel	Increased fuel flow rate enlarged nozzle holes	Single cylinder DI engine, 3.82" bore, 5.04" stroke CR=17:1, no rated speed given	BSFC very similar to baseline No. 2 diesel, BSFC is proportional to 1/BTE	BMEP very similar to baseline No. 2 diesel, BMEP is proportional to BHP at constant speed	Assumed o.k. since addition of nitrates leads to same ID as diesel	Less HC and black smoke than diesel No. 2 diesel below 40% speed capacity, NO_x diesel @ higher speeds	[illegible] than diesel	[illegible]
Alcohol/diesel fuel (ethanol)	Alcohol fumigated w simultaneous diesel fuel injection	Atomization nozzle ified for fumigant	4-cyl, 6-bhp diesel, 3" bore, 3.0625" stroke, 21.7CID, CR=18:1, rated speed=3000 rpm tests run at very high speed (2400 rpm)	@1/3 rack BTE less than diesel and decreases w/ increasing alcohol percent, @2/3 rack BTE approximates diesel, @ full rack BTE increases above diesel w/increased alcohol substitution	Not monitored	[illegible] substitution w fumigated alcohol before ignition failure or excessive knock, knock was intense during portions of tests at all loads, knock incr. w incr. alcohol	NO_x diesel @ full load, approx. = diesel at 2/3 load and diesel at 1/3 load, lower proof alc. had less emissions, CO approx. diesel @ full load, above diesel @ 1/3 and 2/3 load, incr. w/incr. alc. subst. particulates down w/incr. alc. subst.	Limited visual [illegible] normal wear [illegible] combustion [illegible] and piston	[illegible] ethanol performed better
Alcohol/diesel fuel/cetane improvers(No.2, No.4, HVO, ethanol, butanol, improvers)	Blends premixed and injected with existing injection sys.	None	4-cyl, 4-stroke, DI engine, 3.31" bore, 4.13" stroke, CR=16.5:1, rated bhp=41.57 tests run at very high speed (1754-2193 rpm)	Lower than diesel at medium and light loads, approximates diesel at full load	Diesel near 2.9[illegible] rpm, approximate diesel at mid range 1900 rpm and lower than diesel near [illegible] rpm	Increased knocking over diesel but not considered intolerable, knock decreased w increasing equivalence ratio	Less smoke than No. 2 diesel. CO, HC, NO_x not monitored	Not monitored	Lower exhaust temperatures than diesel, less [illegible] than diesel [illegible]
Water diesel fuel emulsions	Direct substitution for diesel fuel	None	12-cyl, 4-stroke, 171[illegible]CID, 5.5" bore, 6" stroke, 8[illegible] hp, 2300 rated speed and a 12 (16) cyl, 2-stroke 5.75" bore, 1733CID, 900(1200) hp 1800 rpm rated speed engine	An emulsion of 15-20% water produced a 2.5% fuel savings in the 4-stroke; no reduction in fuel consumption could be achieved in the 2-stroke	Not monitored	Not monitored	Lower opacity of smoke, but no high smoke levels	Not monitored	Small fuel savings [illegible] the lab are assumed negligible in the
Diesel fuel/raw coal slurry samples of 20, 32,40% coal	Direct substitution for diesel fuel	None	1-cyl, 4-stroke, 14.75 hp, 4.5" bore 5.25" stroke, 82.99CID, CR=15:1, rated speed=1800 rpm tests run at 1430 rpm, high speed	BSFC increased with increased coal percentage	Lower than diesel with rapid decline w.increased coal percentage	Not monitored	SO_x and NO_x higher than diesel	Large amounts of wear on rings, piston, cylinder lining and injection nozzle, wear deemed intolerable	
Diesel fuel/raw coal slurry	Direct substitution for diesel fuel	None	29.92" bore, 61.02" stroke, CR=10.63:1, 1972.6 hp, rated speed=120 rpm, all tests performed at 120 rpm, slow speed	BSFC greater than diesel, slurry testing increases fuel consumption of future diesel runs	Not monitored	ID greater than diesel but no knocking problems reported	Black smoke and NO_x greater than diesel	Heavy wear on injection nozzles, [illegible] rings	
COED (liquified coal based fuel)	Direct substitution for diesel fuel	None	29.92" bore, 61.02" stroke, CR=10.63:1, 1972.6 hp, rated speed=120 rpm, slow speed testing at 120 rpm	BSFC paralleled diesel values with small magnitude difference	Not monitored	ID close to diesel, no knock problem noticed, ID decreased with increasing load	Smoke emissions close to diesel values at invisible level, NO_x and CO greater than diesel, HC lower than diesel	Not monitored	Coal needs [illegible] refinement to produce COED

Table 8 (Cont'd)

Fuel	Combustion technology	Retrofit requirements	Test engine specifications	BTE or related factors	Power output or related factors	Knock	Emissions	Engine wear	Other
SRC-II (solvent refined coal) w 3.5% diesel pilot	Substitution for diesel fuel w pilot diesel injection	Added injector for a diesel pilot	29.92" bore, 51.42" stroke, CR=13.63:1, 1972.6 hp, rated speed = 120 rpm, slow speed testing at 120 rpm	BSFC close to baseline diesel but still higher	Not monitored	No knock problem with diesel pilot	NO_x above diesel	Attacks rubber hoses and o-rings	
Hydrogenated soybean oil	Startup executed w diesel fuel, engine then switched to soybean oil, various nozzles tried	The standard injection nozzle was investigated in addition to a larger and smaller nozzle, no appreciable benefits were achieved w retrofit nozzles, a diesel startup sys. may be needed	1 cyl, 3.74" bore, 3.74"stroke CR=17:1, rated speed=2800 rpm	Very little difference bet. soybean and diesel, generally just below diesel values for std. and larger nozzles, just above baseline for smaller nozzle	100% power output achieved w std. nozzle and larger nozzle 80% power output achieved w smaller nozzle	Fuel type did not affect noise production	Less smoke than diesel w std and enlarged nozzle, more smoke than diesel w small nozzle, NO_x generally less than diesel, HC approx.= diesel	Gum deposits found in combustion chamber and carbon buildup on injection spray tip, long-term effects were not monitored	No testing on potential fuel problems such as waxing, stability, and microbiological attack, large nozzle has 23% more x-sectional area than std, smaller nozzle has 24% less area than std, startability not monitored
Peanut oil	Startup executed w diesel fuel, engine then switched to peanut oil, various nozzles tried	The standard injection nozzle was investigated in addition to a larger and smaller nozzle, no appreciable benefits were achieved w retrofit nozzles, a diesel startup sys. may be needed	1 cyl, 3.74" bore, 3.74"stroke, CR=17:1, rated speed=2500 rpm	Equal to or better than diesel fuel under most operating conditions	90% of diesel output was reached w/std. nozzle, and smaller nozzle, 100% hp delivered w larger nozzle	Fuel type did not affect noise production	Less smoke than diesel w std and enlarged nozzle, more smoke than diesel w small nozzle, NO_x generally less than diesel, HC approx.= diesel	Gum deposits found in combustion chamber and carbon buildup on injection spray tip, long-term effects were not monitored	No testing on potential fuel problems such as waxing, stability, and microbiological attack, large nozzle has 23% more x-sectional area than std, smaller nozzle has 24% less area than std, startability not monitored
Waste vegetable oil/No. 2 diesel fuel (20-80% blend)	Fuel blend premixed and substituted for standard fuel, field test in school bus	None	GM 6V-71, 2 cycle, 426 CID, 5" stroke, 4.25" bore, CR=17:1	Fuel economy approximately the same as diesel	No problems in achieving desired output reported	No information reported	Slight increase in smoke opacity, NO_x, HC, and [illegible] monitored	Tolerable levels of carbon buildup did not impair operation, solidification of fuel at 2°F, toluene solvent required to clear blockage	
Vegetable oil/ alcohol (soybean/ ethanol) [illegible] and nonionic tried	Blend substituted for diesel fuel, diesel or ether assisted ignition required	Diesel or ether start required	3 cyl, 147CID, rated hp=35.27, rated speed = 2400 rpm	Slightly higher than diesel, but BSFC is higher due to higher fueling rates	Within 5% of baseline fuel	No increase over diesel noise	Not monitored	Not monitored	Poor stability, low flash point, might not be cost-effective

3 COAL

The relative abundance of U. S. coal reserves has raised hopes for the possibility of coal-fueled diesels. Most experiments with raw coal have not produced promising results; liquified coal fuels, however, are feasible substitutes but will require substantial refinement.

Marshal, et al., fueled a diesel engine with slurries of No. 2 diesel fuel and raw coal.[21] The test engine was a single-cylinder, four-stroke, 14.75-hp (11-kW) engine with a 11.43-cm (4.5-in.) bore, 13.34-cm (5.25-in.) stroke, displacement of 1360 cc (82.99 cu in.), 15:1 CR, and 1800-rpm rated speed. Three sample fuels containing 20, 32, and 40 percent by weight coal were examined with particles of average diameter equal to 30 microns (1.2×10^{-3} in.). Runs of straight No. 2 diesel fuel were conducted for baseline values; Lower Freeport seam coal was used for the 20 and 40 percent slurries, whereas the 32 percent slurry was made from Pittsburgh seam coal. Figure 11 shows compositions of these coals.[22]

Power output, energy consumption, and emissions were monitored during the test. Engine parts were measured before and after testing to determine wear. All fuel types were run through the engine for 10 hr except for the 40 percent blend; trials with that mixture were stopped after 1 hr because of extremely poor performance. For each test, engines were run at full rack and 1400 rpm.

Figures 12 and 13 depict the power output and BSFC of trial slurries and baseline diesel fuel.[23] The power output declined rapidly as higher coal concentrations were used. Moreover, energy consumption increased with increased coal concentration, thus requiring faster fuel flow rates. Mass and energy calculations suggested that coal particles were practically inert. One theory for the poor coal combustion suggests that the diesel fuel ignites first and the coal is left to burn on the expansion stroke with depleted oxygen. These tests were with a high-speed engine, however; slower engines might perform better because they provide more time for combustion.

Figures 14 and 15 show emissions of sulfur and nitrogen oxides, respectively.[24] Substantially higher concentrations of these pollutants were detected for the slurries than for the diesel fuel. Emission problems, coupled with increased wear, further dim the prospects for use of coal fuels in the near future. For example, unreasonably high amounts of wear were reported for the rings, piston, and lining. The injection nozzle was lodged open with coal and

---

[21] H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 (SAE, 1981), pp 59-70.
[22] H. P. Marshal, et al., p 60.
[23] H. P. Marshal, et al., p 62.
[24] H. P. Marshal, et al., p 65.

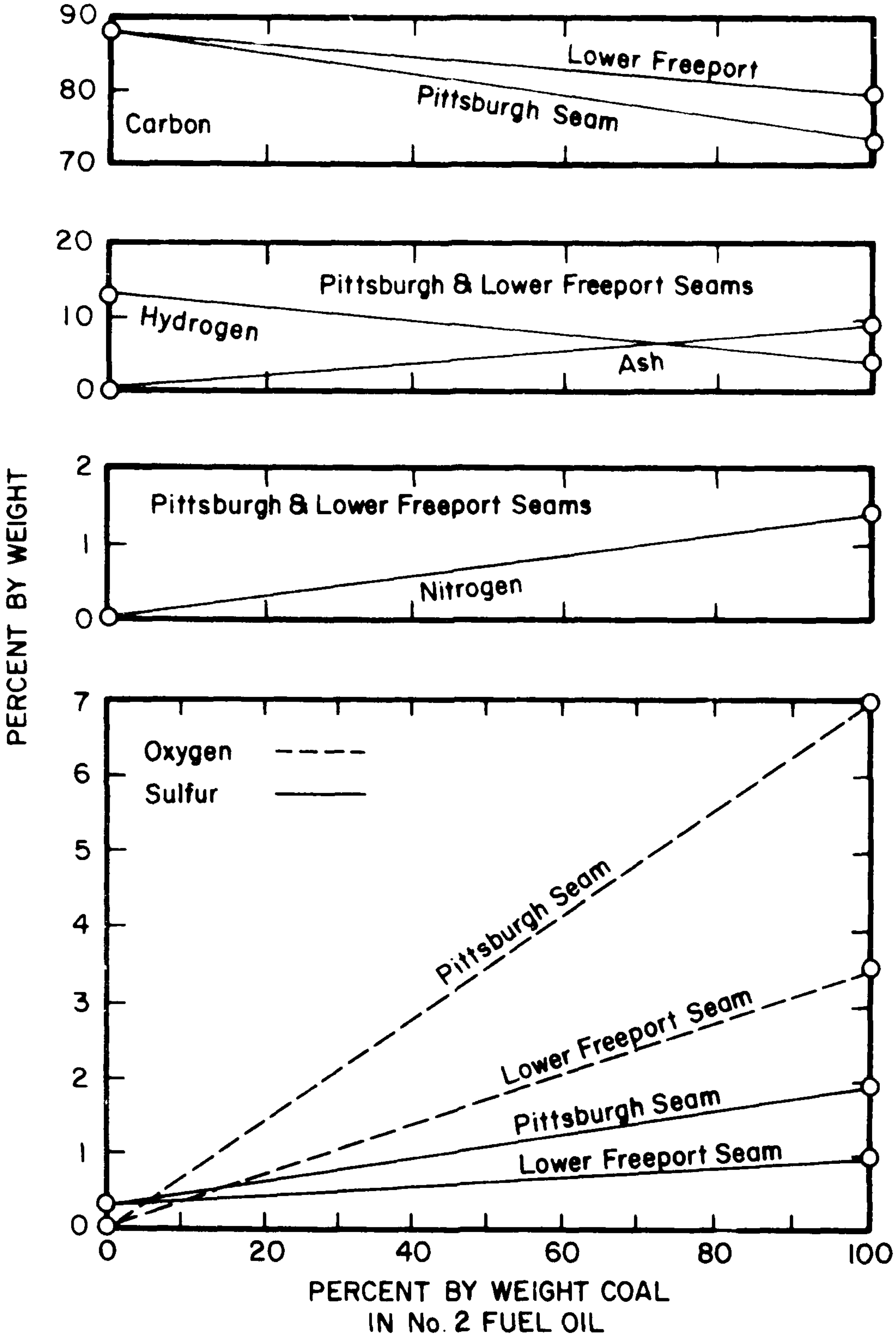


Figure 11. Chemical analysis of micronized coal in oil, moisture free basis. (Source: H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 60.)

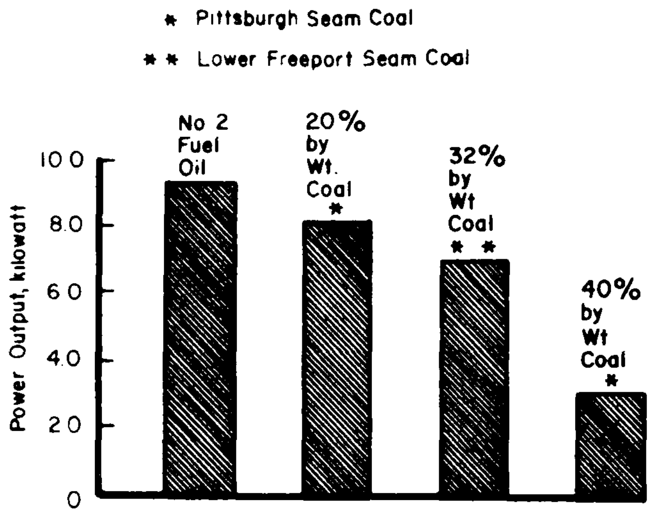


Figure 12. Power production of a single-cylinder 1360-cc diesel engine operating at full rack and 1400 rpm on raw coal-No. 2 fuel oil slurries. (Source: H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 62.)

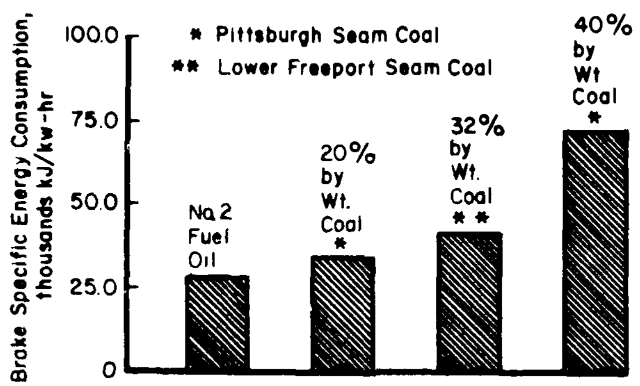


Figure 13. Energy consumption of a single-cylinder 1360-cc diesel engine operating at a full rack and 1400 rpm on raw coal--No. 2 fuel oil slurries. (Source: H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 62.)

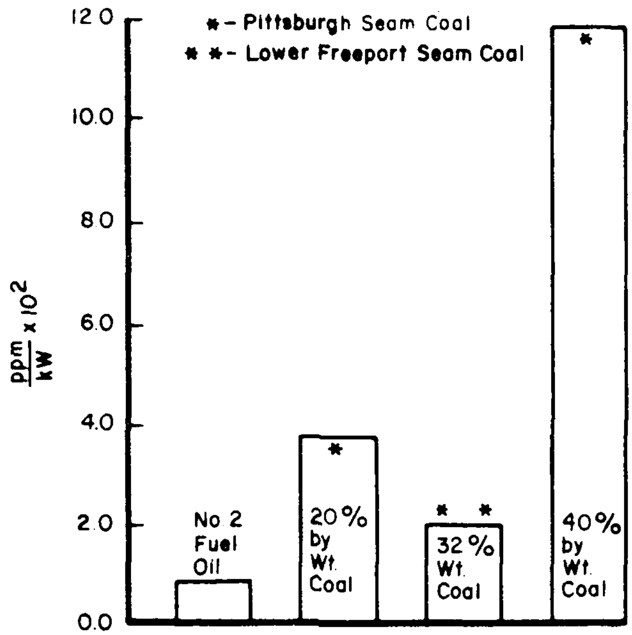


Figure 14. Comparison on power basis of amount of SO_x compounds in exhaust of a single-cylinder, 1360-cc diesel engine operating at full rack and 1400 rpm on raw coal--No. 2 fuel oil slurries. (Source: H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 65.)

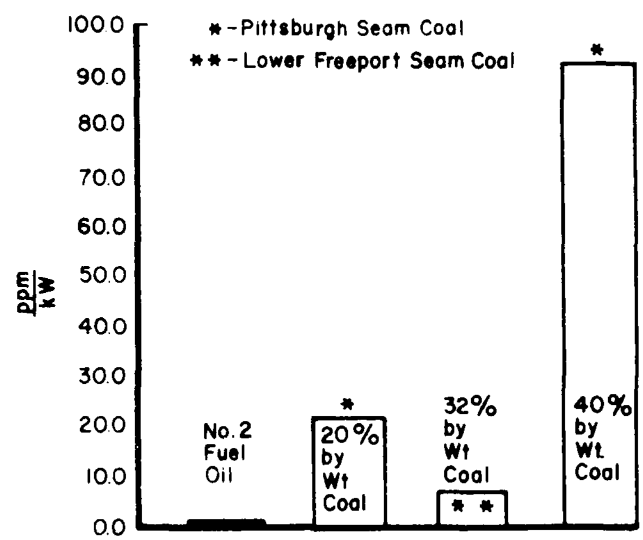


Figure 15. Comparison on power basis of amount of nitrous oxides in exhaust of a single-cylinder, 1360-cc diesel engine operating at full rack and 1400 rpm on raw coal--No. 2 fuel oil slurries. (Source: H. P. Marshal, et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 [Warrendale, PA: SAE, 1981], p 65.)

a thorough coating of coal was discovered over the combustion chamber with the high-concentration slurries.

Dunlay, et al., burned diesel oil-coal slurries in a large, slow-speed engine with somewhat better results.[25] Table 9 shows the composition of their blend,[26] and Figure 16 gives specifics on coal particle sizes.[27] This fuel was tested in an engine with a 760-mm (29.92-in.) bore, 1550-mm (61.02-in.) stroke, 10.63:1 CR, 120-rpm rated speed, and 1471 kW (1972.6 hp).

Fuel could not be injected successfully with the standard Bosch-type injection system. Pump seizure and blockage of the pump plunger and valve stem

Table 9

Coal/Oil Slurry Specifications

Ultimate Analysis (%)	Coal (As Received)*	Diesel Oil No. 2	Coal/Oil Slurry (As Used)**
Lecithin	-	-	1.42
Moisture	1.6	-	0.50
Hydrogen	4.4	13.3	10.30
Carbon	79.8	85.9	82.76
Nitrogen	1.4	0.02	0.46
Oxygen	3.3	-	1.04
Sulfur	1.0	0.78	0.84
Ash	8.5	-	2.68
Heating Value (Btu/lb)			
HHV	14,013	19,410	17,432
LHV	13,585	18,258	16,524

Source: J. B. Dunlay, et al., Performance Tests of a Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-77-C-01-2647 (U.S. Department of Energy, June 1980), p 34.

*Coal type was Lower Freeport Pennsylvania Seam.
**Slurry was prepared by Union Process, Inc., Akron, OH. Content by weight was: 67.03% diesel oil, 35.55% coal, and 1.42% lecithin.

[25] J. B. Dunlay, et al., Performance Tests of a Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-77-C-01-2647 (U.S. Department of Energy, June 1980).
[26] J. B. Dunlay, et al., p 34.
[27] J. B. Dunlay, et al., p 35.

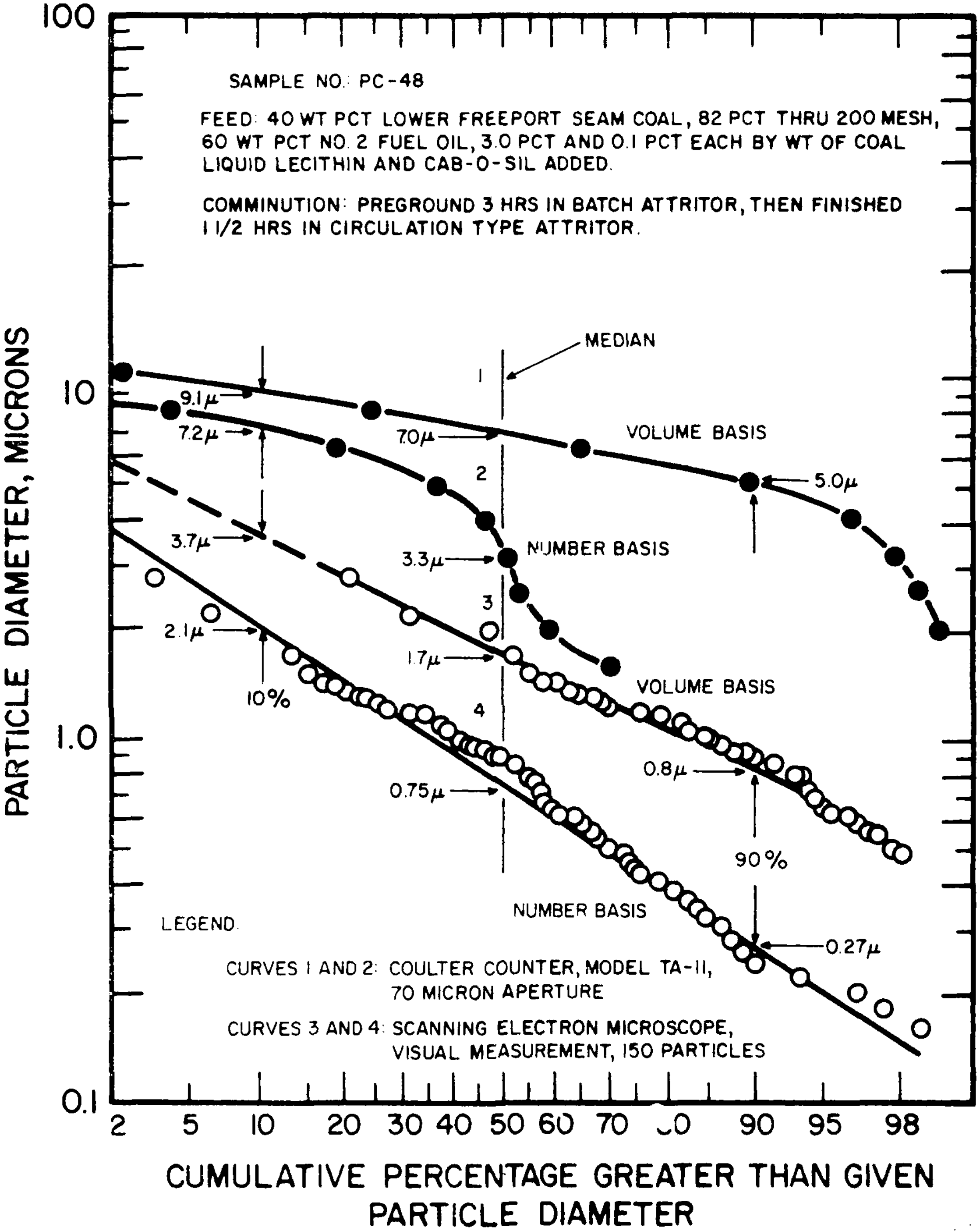


Figure 16. Particle size distribution of micronized coal in oil (MICO). (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 35.)

necessitated a replacement injection system. The substituted accumulator injection system performed satisfactorily. In this setup, a diaphragm pump sends fuel to an accumulator, where it is later metered by a hydraulically operated injection valve.

Although unhampered engine startup and shutdown on coal/oil slurry were demonstrated during the experiment, data taken before and after slurry tests on diesel fuel revealed performance deterioration as evidenced by the diesel fuel's increased BSFC. The slurry caused heavy wear on the injection nozzles and wear and binding on piston rings. Lubrication scouring of the cylinder liner was predicted to cause future problems.

Even with hourly changes of the injection nozzle, the diesel fuel heat rate increased. Therefore, ring condition was considered the major factor in increased fuel consumption. The diesel fuel heat rate after the slurry test was up 2.5 to 4.6 percent of preslurry test values.

Figures 17 and 18 show experimental results of slurry and diesel runs.[28] BSFC, black smoke, and nitrous oxides emission for slurry tests was greater than for diesel runs. Ignition lag was also greater, but no knocking was reported. Dunlay's group did not suspect unreasonably delayed or incomplete combustion as seen in the high-speed slurry test.

Dunlay, et al., also investigated fuels derived from liquified coal, including char oil energy development (COED) fuel and solvent refined coal (SRC-II) fuel. Table 10 gives fuel analyses and compares them with diesel fuel.[29] The same engine used in the diesel/coal slurry experiment was used.

Performance indicators such as BSFC, smoke emissions, and ignition lag were monitored with variable engine loads, while timing, injection pressure, and air pressure remained constant. COED fuel paralleled baseline diesel [illegible] these parameters (Figure 19).[30] BSFC decreased with increasing load for both COED and baseline diesel. Smoke emissions remained at a fairly [illegible] level throughout testing. Ignition lag decreased with increasing load. Delay was longer for the COED fuel than for the diesel, but [illegible] differences of the values were very slight. Knocking was not a problem during COED fuel combustion. Additional testing with COED showed results parallel to diesel with variable injection timing, injection pressure, and air pressure.

---

[28] J. B. Dunlay, et al., pp 41-42.
[29] J. B. Dunlay, et al., p 22.
[30] J. B. Dunlay, et al., p 16.

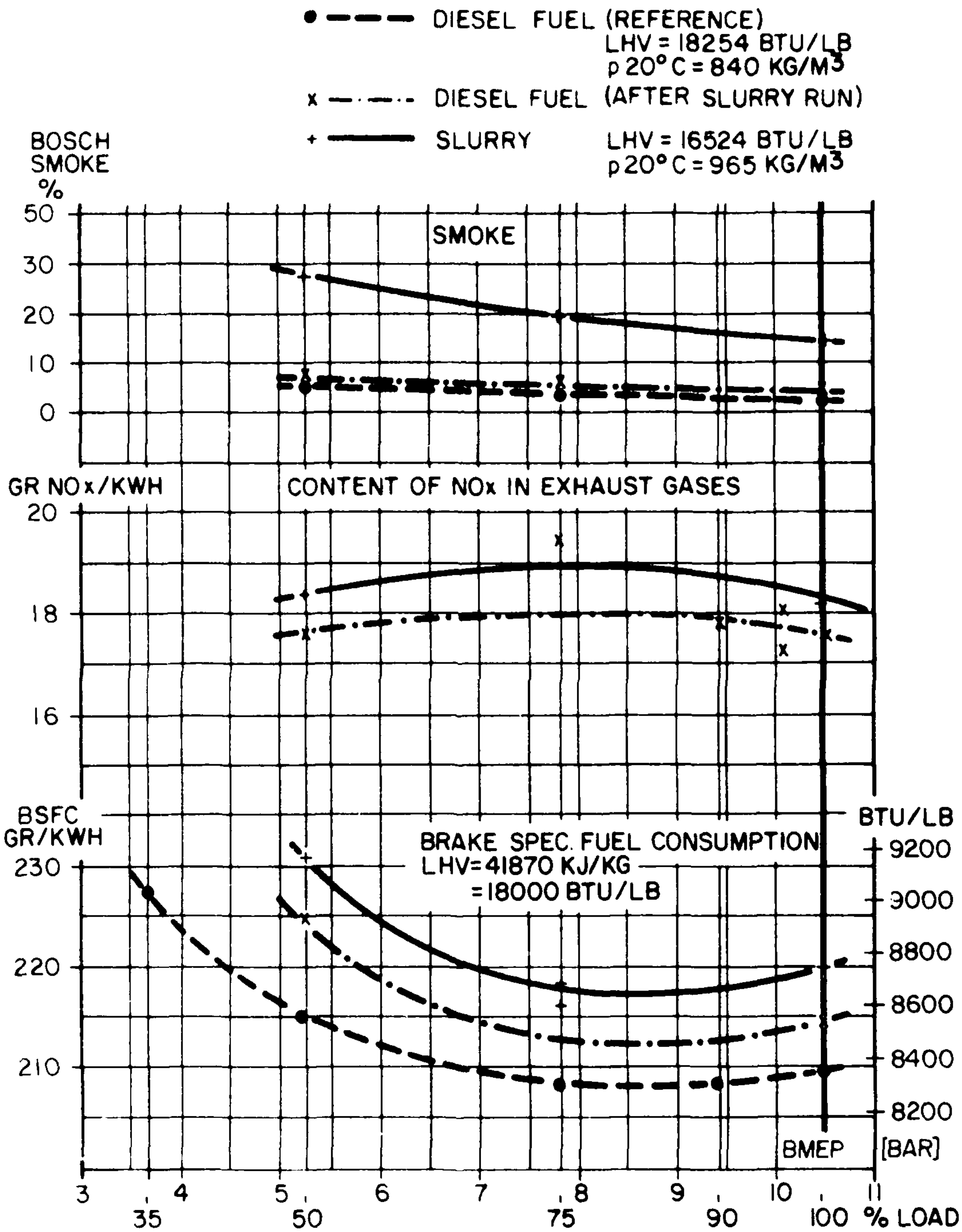


Figure 17. Tests with coal oil slurry. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 41.)

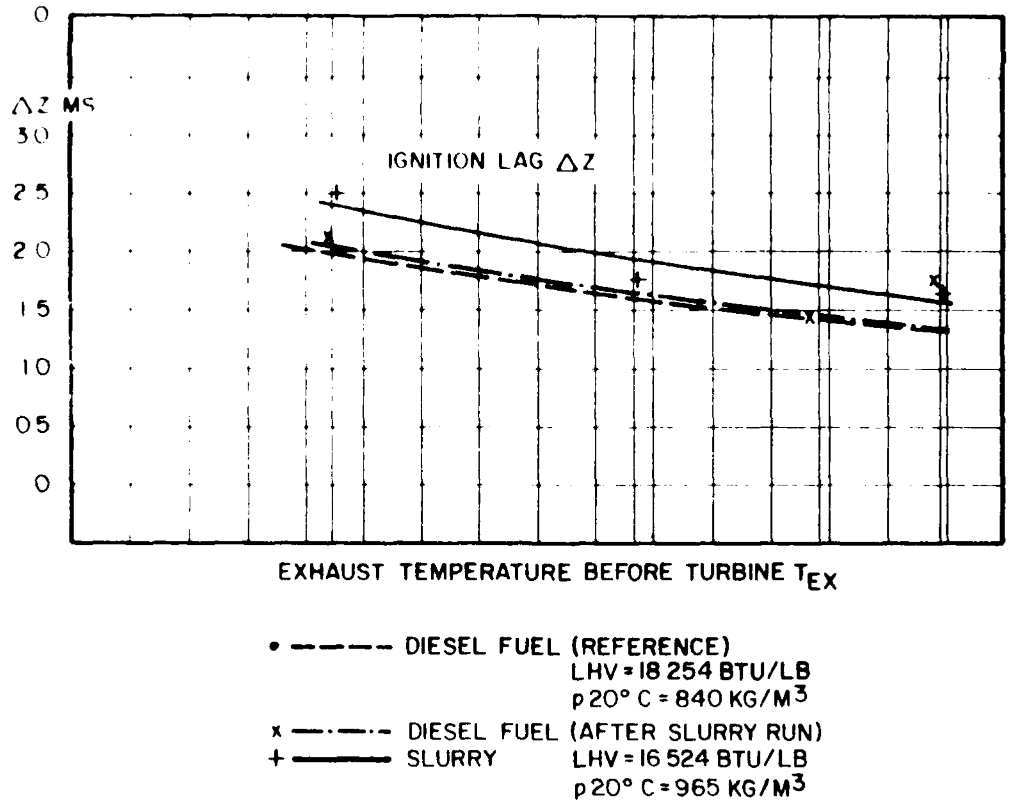


Figure 18. Tests with coal/oil slurry at constant speed = 120 rpm. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 42.)

Figure 20 shows emissions from the COED normalized to emissions of diesel fuel at full load.[31] Nitrous oxides and carbon monoxide emissions were greater for COED, but hydrocarbon emissions were lower than for diesel exhaust. Overall, COED fuel imitated diesel performance reasonably well without engine modification. Refinement costs to produce COED from coal were considered economically prohibitive in an earlier report by Dunlay,[32] with COED's high hydrogen content cited as a major expense.

SRC-II fuel has a very low CN of 0.8. Trial runs with this fuel produced severe knocking due to poor ignition quality. Various methods of improving combustion were attempted, such as blending with diesel oil, elevating air and cooling temperatures, preinjecting SRC-II, and pilot injecting with diesel oil. Combustion performance with the diesel pilot was superior to other alternatives.

Although mixtures of SRC-II and diesel oil produced satisfactory levels of knock with an 80 percent SRC-II/20 percent diesel oil blend running at full

[31] J. B. Dunlay, et al., p 21.

[32] J. B. Dunlay, et al., Economic and Technological Assessment of Diesel Engines Using Coal-Based Fuels for Electric Power Generation, NTIS TE4234-37-80 (U. S. Department of Energy, September 1979).

Table 10

Comparison of Fuel Analysis Data

Analysis	Fuel: SRC-II Sample No. 12082 Dec 78	Diesel Fuel Sample No. 12094	COED Sample No. 12041 Dec 77
Specific gravity at 20°C (g/cm^3)	0.975	0.842	0.935
Viscosity at 20°C (cSt)	5.41	5.55	
Viscosity at 40°C	3.01	2.81/50°	6.78/50°
Refractive index at 20°C	1.5450	-	1.529
Pour point (°C)	-30	-	+21
Flash point in closed cup (°C)	75	82	49
Caloric value (upper) (kJ/kg)	40153	45140	43482
Caloric value (lower) (kJ/kg)	38227	42460	40890
Content of:			
- Carbon (%)	86.7	85.9	88.9
- Hydrogen (%)	8.95	13.3	10.5
- Sulfur (%)	0.21	0.78	0.13
- Oxygen and nitrogen (%)	4.14	0.02	0.47
- Ash (ppm)	10	80	20
- Water (%)	0.1		<0.1
- Paraffins, naphthenes, aromatics (%)	-	-	39.8/25.8/34.4
Ratio - Hydrogen:carbon	1.229	1.8434	1.407
Conradson carbon residue (%)	0.02	0.04	0.64
Aniline point (°C)	<-15	72	50
Total acid number (mgKOH/g)	0.11	-	-
Diesel index	0.7	58	23
Cetane number	0.8	54	30
Boiling analysis at atmospheric pressure (°C)			
Initial boiling point	158	204	117
5 Vol. % boiling up to	195	-	130
10 Vol. % boiling up to	202	235	≈202
20 Vol. % boiling up to	208	250	≈250
30 Vol. % boiling up to	213	[illegible]	[illegible]
40 Vol. % boiling up to	218	270	[illegible]
50 Vol. % boiling up to	224	[illegible]	[illegible]
60 Vol. % boiling up to	[illegible]	290	[illegible]
70 Vol. % boiling up to	[illegible]	302	[illegible]
80 Vol. % boiling up to	[illegible]	[illegible]	-
90 Vol. % boiling up to	[illegible]	336	-
Up to 350°C are distilled (vol %)	[illegible]	94.5	[illegible]

Source: J. G. Dunlay, et al., Performance [illegible] Diesel Engine Using [illegible], [illegible], Contract No. EF-77-C-01-2647 (U.S. Department of Energy, June 1980), p 34.

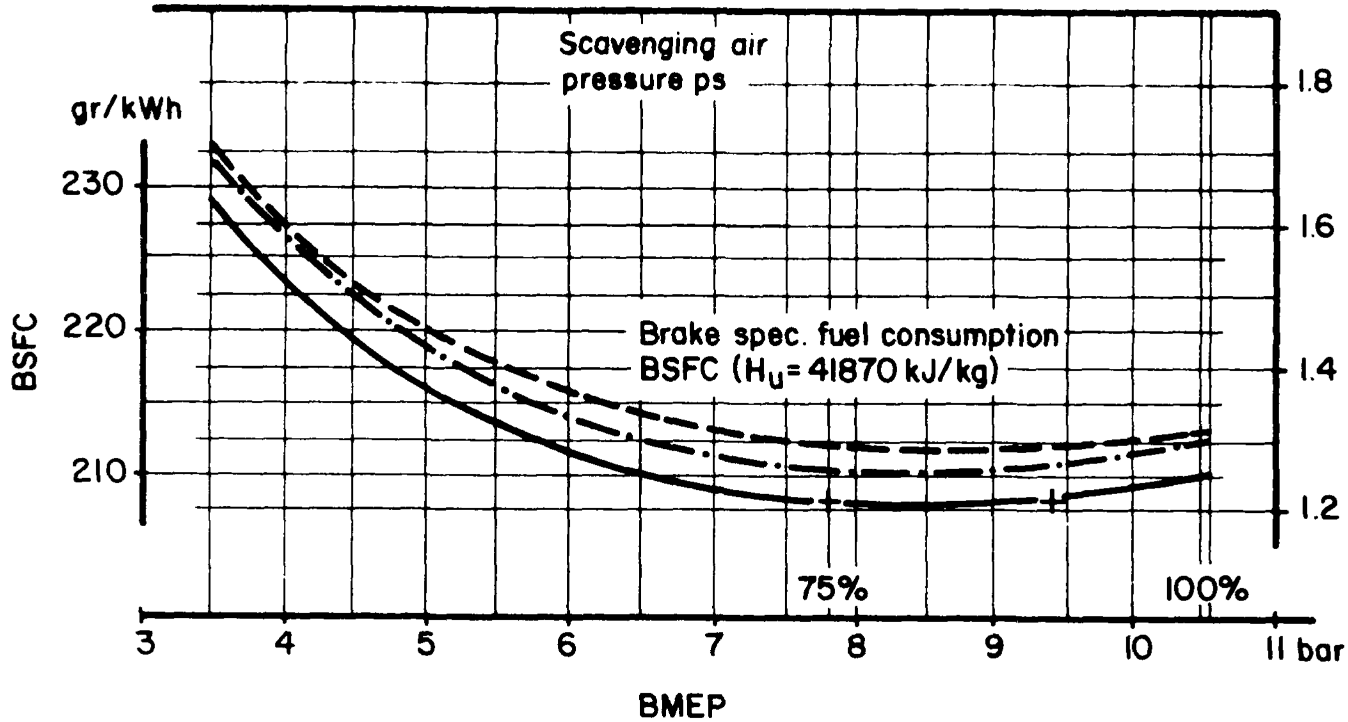


Figure 19. COED tests--Variable load. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 16.)

load, lower load settings intensified the knock to intolerable levels. Lesser concentrations of diesel oil had the same effect (Table 11).[33] Through trial and error, optimal ignition delay periods for this engine were set at 2.5 and 3.0 ms. It was noted that faster engines would need shorter delays for smooth combustion and would thus require more diesel oil in the mixture.

Experiments with elevated temperatures were conducted with a blend of 10 percent diesel oil and a 75 percent load. Increasing air, fuel, and coolant temperatures did not lower ignition delay times to an acceptable level. Table 12 shows the resulting delay periods.[34] Full-load trials at elevated temperatures were not attempted.

Varied conditions when preinjecting a small amount of SRC-II led to similar disappointment. The shortest delay achieved still produced significant knocking.

Injecting a small amount of diesel oil to pilot SRC-II combustion produced quality (low-knock) burning at all load settings. On average, 3.5 percent

[33] J. B. Dunlay, et al., 1979, p 25.
[34] J. B. Dunlay, et al., 1979, p 26.

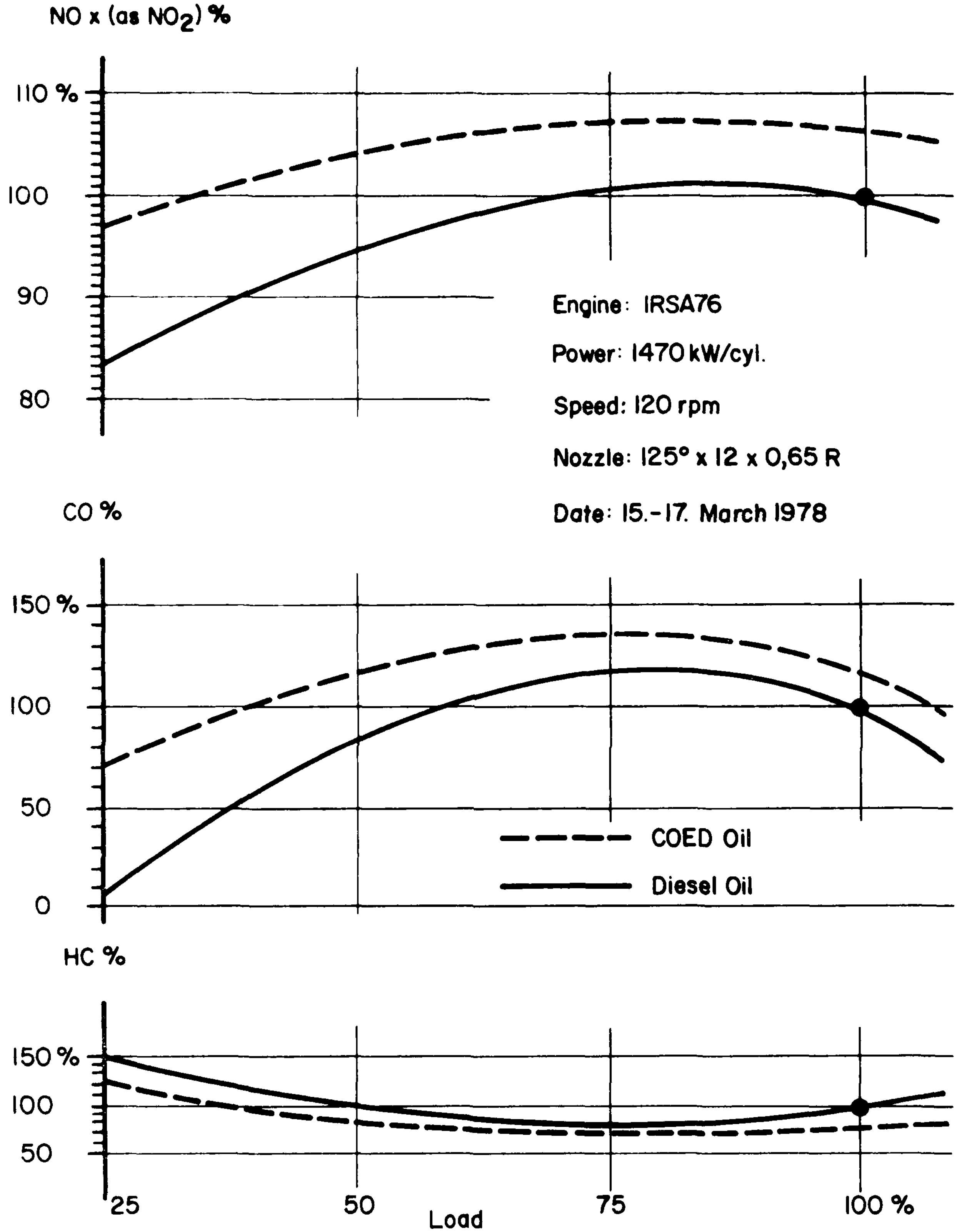


Figure 20. COED exhaust gas emission measurements. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 21.)

Table 11

Ignition Delay Time and Knocking Sound With
Fuel Mixing and Engine Load
(Room Temperature Fuel)

Engine Load (%)	Diesel Oil Content (%)	Ignition Delay (ms)	Knocking Sound
90	100	0.8	Normal
	20	2.6	Normal
	10	4.3	Hard
	7	6.2	Very hard
75	10	8.7	Extremely hard

Source: J. B. Dunlay, et al., Performance Tests of a Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-77-C-01-2647 (U.S. Department of Energy, June 1980), p 34.

Table 12

Ignition Delay Time Improvements With Elevated
Temperatures and Preinjection
(10% Diesel Oil, 75% Load)

Test Condition	Ignition Delay (ms)
Normal	
Air temp. 40°C	
Cylinder cooling temp. 48/62°C (in/out)	8.7
Piston cooling temp. 36/45°C (in/out)	
Fuel temp. 25°C	
Air temp. increased to 70°C	5.8
Cylinder cooling temp. increased to 63/75°C (in/out)	5.5
Piston cooling temp. increased to 47/60°C (in/out)	
Fuel temp. increased to 50°C (injection timing changed)	8.95
135°C	4.0
165°C	3.5
195°C	3.5
Preinjection	4.2

of the total fuel injection was found to be an adequate fraction of pilot diesel oil, resulting in BSFC and smoke values quite close to those of baseline diesel fuel (Figure 21).[35] BSFC was slightly higher than for diesel fuel at all loads, but not unreasonably so. Ignition lag was up to 1.5 ms higher, but still within accepted limits. Piloted SRC-II showed continued increases in nitrous oxide exhaust, whereas diesel fuel output leveled off near 70 percent load and decreased slightly at full load (Figure 22).[36] The greatest separation of values occurred at 100 percent load; here, data differed by 5 g/kWh (8.22×10^{-3} lbm/hp-hr).

Even with the noted deviations of SRC-II from diesel oil standards, quite acceptable performance was demonstrated in a slow-speed diesel. Emission standards and reinforcement cost would need to be reviewed before large-scale use of this fuel, however. Also, SRC-II attacks rubber hoses and O-rings, a tendency that may prevent long-term runs or necessitate retrofits with different material rings and hoses.

To summarize, solid coal slurries and solvent-refined coal are not up to par with expectations for fuel alternatives. Slurries caused wear problems at all loads and speeds, and combustion performance deteriorated substantially from diesel baselines. Injection and pumping problems required special attention.

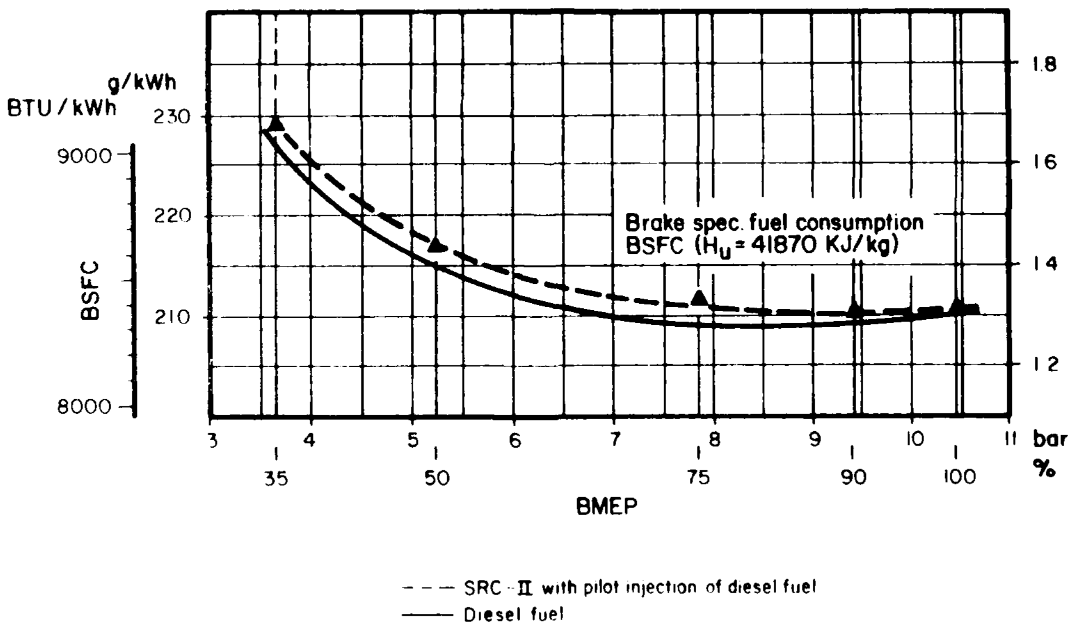


Figure 21. Experimental results obtained with SCR-11 at constant speed n = 120 rpm. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 29.)

[35] J. B. Dunlay, et al., 1979, p 29.

[36] J. B. Dunlay, et al., 1979, p 31.

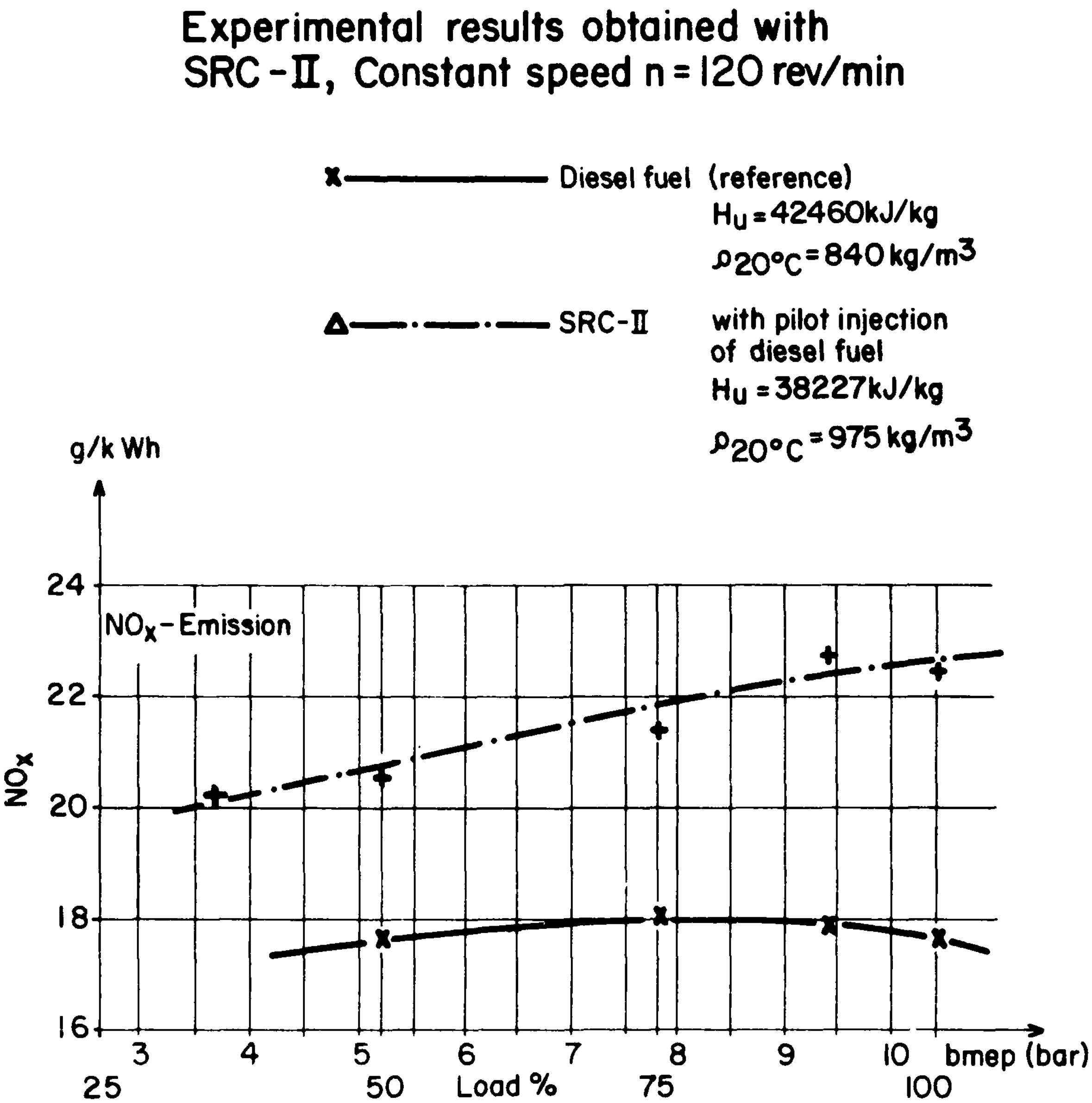


Figure 22. Tests with coal-derived fuels. (Source: J. B. Dunlay, et al., Performance Tests of Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-11-C-01-2647 [U.S. Department of Energy, June 1980], p 31.)

SRC-II was far superior to slurry trials, but not as promising as COED. Although SRC-II performed similarly to diesel fuel in terms of combustion, it did require pilot injection and monitoring for corrosion on rubber hoses and rings.

Of the coal fuels, COED is the most feasible substitute. COED performed similarly to diesel fuel with regard to BSFC, smoke emissions, and ignition delay. Knocking was not a problem at any load. Nitrous oxides and carbon monoxide emissions were above those of diesel exhaust, though, and a review of ambient air laws would be in order before using this fuel. It must be noted that COED was tested with a slow-speed diesel (120 rpm); faster engines may not perform as well. Table 8 summarizes experimental results from the coal fuels.

4 VEGETABLE OILS

Vegetable oils are a renewable source of fuel, with peanut and soybean oils especially popular due to domestic availability. Their use in diesel engines has long been investigated. In 1900, Dr. Rudolph Diesel powered one of his engines with peanut oil at the Paris Exposition. Since then, numerous attempts have been made to adapt the diesel engine to attain satisfactory combustion with vegetable oils. Single fueling with vegetable oils has been tried with varying results. Some other fuel usually is introduced to assist in ignition; it may then be replaced by the vegetable oil or may be present during all combustion via a dual injection system or premixing.

Trials with single fueling by vegetable oil following a diesel fuel start have been quite encouraging, except where power output is of prime importance. Since these oils have a lower energy content than diesel fuel, equal fuel flow rates will yield a lower power output unless the engine is modified. For example, redesigned injection equipment or modified injection sprays could produce the desired results.

Forgiel and Varde investigated fueling the direct injection diesel engine with vegetable oils using various injection nozzles.[37] They evaluated engine performance in terms of power output, brake thermal efficiency, and emissions, and monitored the changes in these parameters with different nozzles. All tests were conducted on a one-cylinder, naturally aspirated, air-cooled engine with a 95-mm (3.74-in.) bore, 95-mm (3.74-in.) stroke, 17:1 CR, and a rated speed of 2800 rpm. The naturally aspirated engine was chosen for its increased ignition delay and sensitivity to fuel quality.

Three different nozzles were used in the experiment--the standard injector with four orifices, nozzle B, and two other nozzles, A and C, with approximately 25 percent more and 24 percent less cross sectional area, respectively (Table 13).[38]

The fuels used were No. 2 diesel, 100 percent hydrogenated soybean oil, and 100 percent peanut oil. Tables 14 and 15 give properties of these fuels and other vegetable oils.[39] All test points were taken during steady-state conditions. Starts were executed with diesel fuel and then the engine was switched to the experimental fuel; it was switched back to No. 2 diesel before shutdown. At no time was the engine allowed to sit while filled with vegetable oil, which sidestepped many potential problems such as waxing, long range stability, and microbiological attack on the fuel.

---

[37] R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternate Fuels for [illegible] Engines SP-503 (Warrendale, [illegible]: SAE, 1981), pp 59-66.

[38] R. Forgiel and K. S. Varde, p 60.

[39] R. Forgiel and K. S. Varde, p 60; C. E. Goering, et al., p 1475.

Table 13

Nozzle Orifices Used in Experiment

	Nozzle A	Nozzle B (OEM)	Nozzle C
No. of orifices	4	4	5
Orifice diameter (mm)	0.36	0.32	0.25
l/d	1.9	2.3	2.8

Source: R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: SAE, 1981), p 60.

Table 14

Properties of Fuels Used in Experiment

	Diesel #2	Soybean	Peanut
Density (g/cc)	.825	.899	.900
Heating value (kJ/kg)	42580	37064	37282
Viscosity @ 24°C (CS)	2.8	39	40.5
@ 43°C (CS)	1.8	10.5	15.0
Cetane no.	46	33	35
Heat of vaporization (cal/g)	61	52	53
Flash point (°C)	60	332	326
Spec. heat @ 38.6°C (cal/g °C)	0.44	0.469	0.490
Surface tension (dynes/cm @ 20°C)	28	33	35

Source: R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: SAE, 1981), p 60.

Table 15

Fuel Properties of Vegetable Oils

Vegetable Oil	Viscosity* (mm^2/s)	Cetane Number**	Hg (kJ/kg) (°C)	Cloud Point (°C)	Pour Point (°C)	Flash Point (°C)	Density (kg/L)	Water and Sediment (%V)	Carbon Residue (%w)	Ash (%w)	Sulfur (%w)	Copper Corrosion	Induction Period (hr)
Castor	297	[illegible]	37274	none	-31.7	260	0.9537	trace	0.22	<0.01	0.01	1a	95.0
Corn	34.9	37.6	39500	- 1.1	-40.0	277	0.9095	trace	0.24	0.01	0.01	1a	9.3
Cottonseed	33.5	41.8	39468	1.7	-15.0	234	0.9148	0.04	0.24	0.01	0.01	1a	7.3
Crambe	53.6	44.6	40482	10.0	-12.2	274	0.9044	0.2	0.23	0.05	0.01	1a	9.0
Linseed	27.2	34.6	39307	1.7	-15.0	241	0.9236	trace	0.22	<0.01	0.01	1a	2.9
Peanut	39.6	41.8	39782	12.8	- 6.7	271	0.9026	trace	0.24	0.005	0.01	1a	6.4
Rapeseed	37.0	37.6	39709	- 3.9	-31.7	246	0.9115	trace	0.30	0.054	0.01	1a	10.0
Safflower	31.3	41.3	39519	18.3	- 6.7	260	0.9144	trace	0.25	0.006	0.01	1a	3.1
H. O. Safflower	41.2	49.1	39516	-12.2	-20.6	293	0.9021	trace	0.24	<0.001	0.02	1a	9.8
Sesame	35.5	40.2	39349	- 3.9	- 9.4	260	0.9133	trace	0.25	<0.01	0.01	1a	8.7
Soybean	32.6	37.9	39623	- 3.9	-12.2	254	0.9138	trace	0.27	<0.01	0.01	1a	7.4
Sunflower	33.9	37.1	39575	7.2	-15.0	274	0.9161	trace	0.23	<0.01	0.01	1a	5.4
Typical No. 2 diesel	2.7	47	45343	-15.0	-33.0	52	0.8400	<0.05	<0.35	<0.01	<0.01	3	>150

Source: C. E. Goering, et al., "Fuel Properties of Eleven Vegetable Oils," Transactions of the ASAE, Vol 25, No. 6 (1982), p 1475.
* Measured at 38°C.
**Measured using a modified form of ASTM D613 in which ignition delays were observed visually.

Performance of the No. 2 diesel fuel with nozzle B was used as the baseline value, with 100 percent load defined as the maximum load at 2800 rpm. Power output was affected by the nozzle and the fuel. The smaller than standard nozzle, C, could produce 100 percent of the baseline power when fueled with No. 2 diesel. With the more viscous soybean oil, this smaller nozzle delivered 80 percent, and with the most viscous peanut oil, 90 percent baseline power was achieved.

The larger than standard nozzle, A, delivered up to 110 percent baseline power with diesel fuel. This setup yielded 100 percent power with both soybean and peanut oils. The higher mass flow rate accommodated by this nozzle is thought to account for the high power output. The standard nozzle, B, reached 100 percent power with soybean oil but only 90 percent with peanut oil.

For power output, the enlarged nozzle performed best. However, the standard nozzle lost only 10 percent of its maximal power output with the peanut oil and none with the soybean oil. This 10 percent loss may be justified to avoid retrofit costs.

BTE was plotted against the load in Figure 23.[40] Under most conditions, the standard equipment nozzle, B, produced the highest efficiency. Little difference was noted between the fuels except when peanut oil was run through nozzle A; here, a measurable increase in BTE was noted. Peanut oil achieved an efficiency equal to or slightly greater than diesel fuel under most operating conditions.

Although the kinetics of smoke formation are not well understood, this property has been correlated with atomization. Greater atomization yields smaller droplet size and tends to reduce smoke production. Since orifice size affects the droplet size, the largest nozzle, A, is predicted to have the greatest amount of smoke formation; nozzle C, the smallest, should have the least. These, in fact, are the effects shown in Figure 24.[41] The standard and the enlarged nozzles produced less smoke with vegetable oils than with diesel fuel. Peanut oil produced the least smoke. For the smallest nozzle, the diesel performed better than the vegetable oils, with peanut oil still producing less smoke than soybean oil. The reason for this inversion in the smallest nozzle is not understood.

Nitrogen oxide emissions are dependent on local mixture concentrations and temperatures, both of which are affected by orifice size. Figure 25 summarizes the nitrogen emissions, revealing that the largest nozzle produced the lowest emissions, whereas the standard nozzle produced the highest concentration of exhaust oxides.[42] Apparently, nitrous oxides production

[40] R. Forgiel and K. S. Varde, p 61.
[41] R. Forgiel and K. S. Varde, p 62.
[42] R. Forgiel and K. S. Varde, p 64.

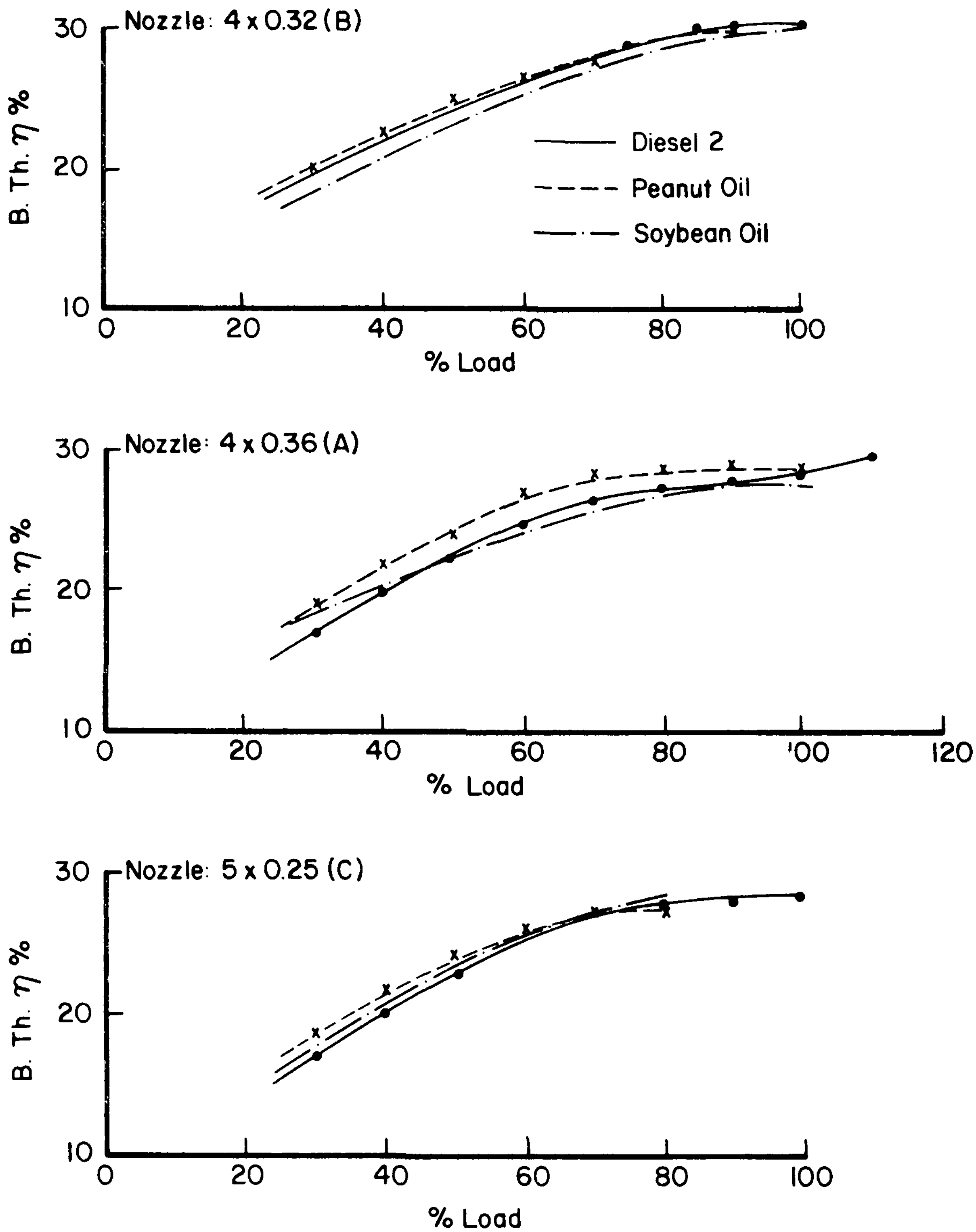


Figure 23. Effects of nozzle and fuel on engine efficiency. (Source: R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternative Fuels for Diesel Engines SP-503 [Warrendale, PA: SAE, 1981], p 61.

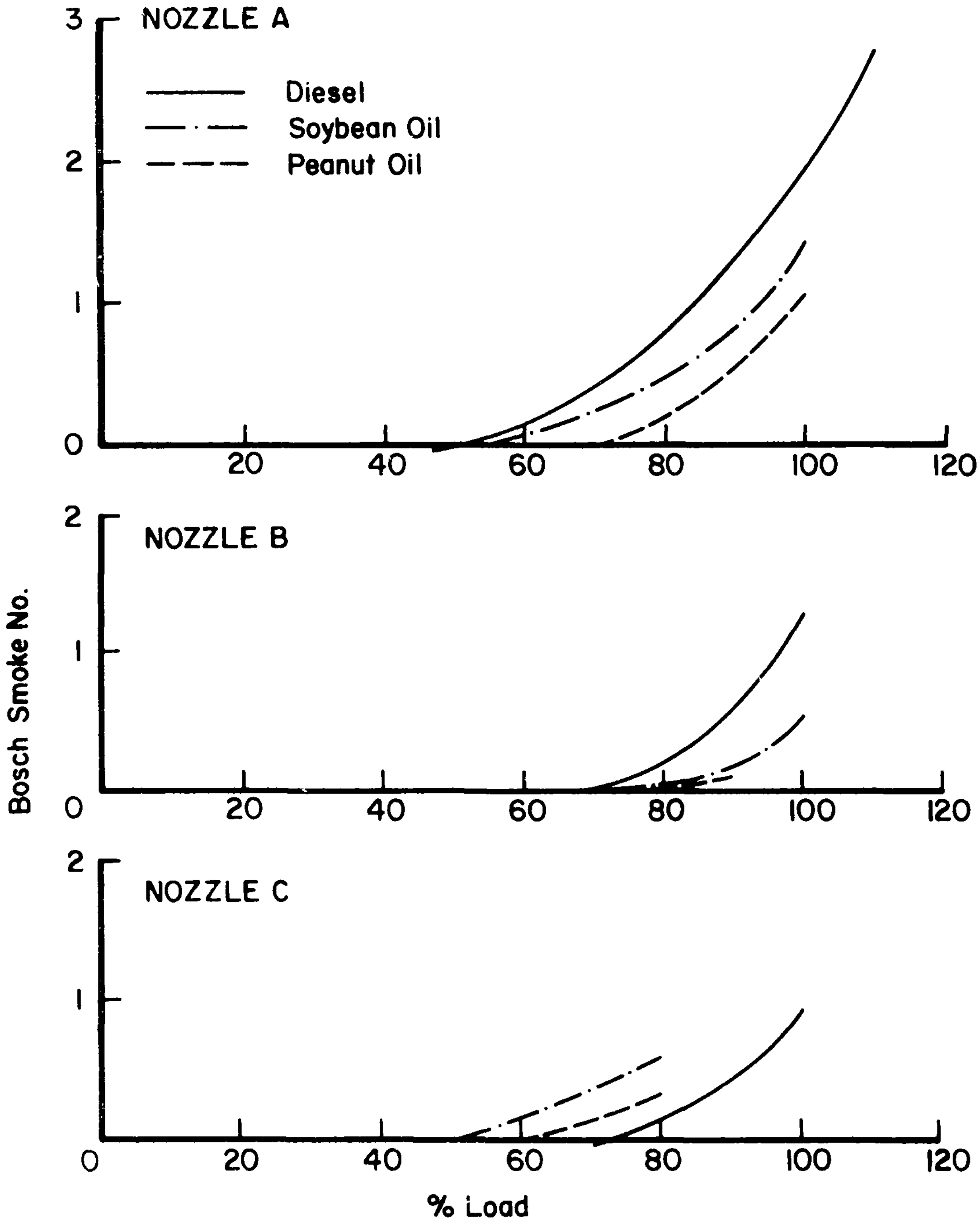


Figure 24. Comparison of smoke levels (Source: R. Forgiel and K. S. Varde. "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternative Fuels for Diesel Engines SP-503 [Warrendale, PA: SAE, 1981], p 62.)

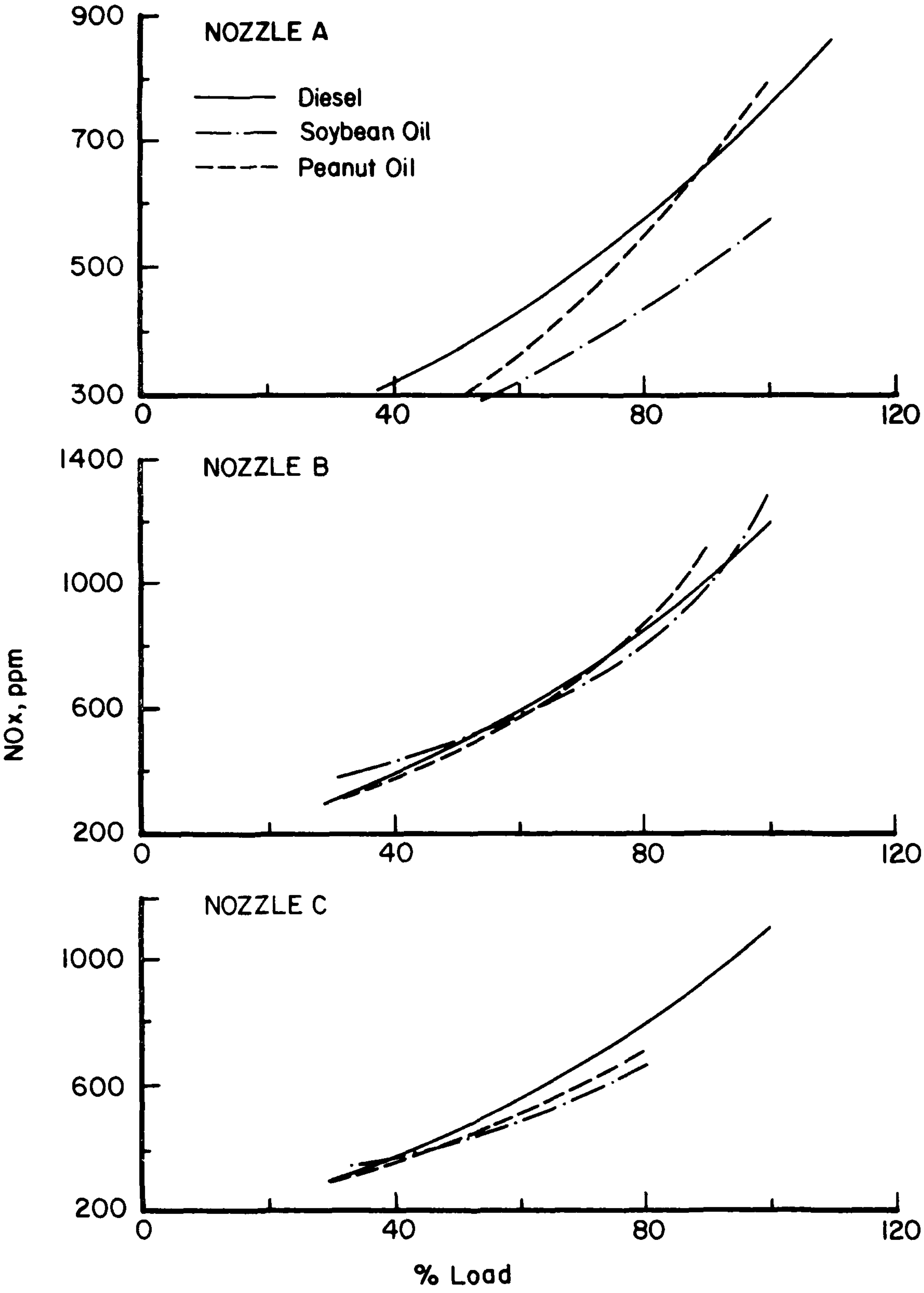


Figure 25. Variation of nitrous oxides (NO_X) emission with different fuels. (Source: R. Forgiel and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternative Fuels for Diesel Engines SP-503 [Warrendale, PA: SAE, 1981], p 64.)

increases with an initial decrease in nozzle size, then decreases with further size reduction.

In general, soybean oil produced the fewest nitrous oxides emissions over the widest range with all nozzles. Peanut oil tended to be in the middle for nitrogen production and diesel was at the top. Little sensitivity to fuel type was detected in the standard and small nozzles. The larger nozzle distributed nitrogen exhaust with the various fuels more than the others. Nitrous oxides emission increased for all fuel types as load increased. For all nozzles and fuels, highest emissions occurred during the most thermally efficient periods.

Hydrocarbon concentrations are graphed against percentage load in Figure 26. Peanut oil emitted the fewest hydrocarbons, whereas diesel and soybean were the top producers, depending on nozzle size.[43]

Noise production and carbon and gum deposits also were checked during testing. For a given nozzle, fuel type did not affect noise levels. After vegetable oil use, the engine was found to have gum deposits in the combustion chamber and carbon buildup on the injection spray tip. Long-term effects of depositions resulting from burning vegetable oils are unknown.

In terms of thermal efficiency and emissions, peanut and soybean oils appear to be viable replacements for diesel fuel during steady-state operation with the standard nozzle. If power output is of prime concern, a larger nozzle may be needed for peanut oil to produce the desired results. Stability and engine wear are two concerns that must be examined before using these fuel alternatives, however.

Fishinger, et al., tested engine durability and fuel-engine compatibility in a study using a premixed blend of vegetable oil and diesel fuel.[44] They monitored a diesel school bus fueled with a 20-80 percent blend of waste vegetable oil and No. 1 diesel fuel. After 4750 miles, results on smoke emissions, fuel consumption, and engine wear were comparable to baseline diesel No. 1 values. Although clouding became a problem at lower temperatures, a toluene solvent alleviated the condition, leading to a strong recommendation for this fuel option.

The test engine was a GM, 6V-71, two-cycle, 426 CID diesel with a 127-mm (5-in.) stroke, a 108-mm (4.25-in.) bore, and a 17:1 CR. This engine powered a bus that averaged 50 miles during 8 hours of continuous running each day.

---

[43] R. Forgiel and K. S. Varde, p 65.

[44] M. K. Fishinger, et al., "Service Trial of Waste Vegetable Oil as a Diesel Fuel Supplement," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: SAE, October 1981).

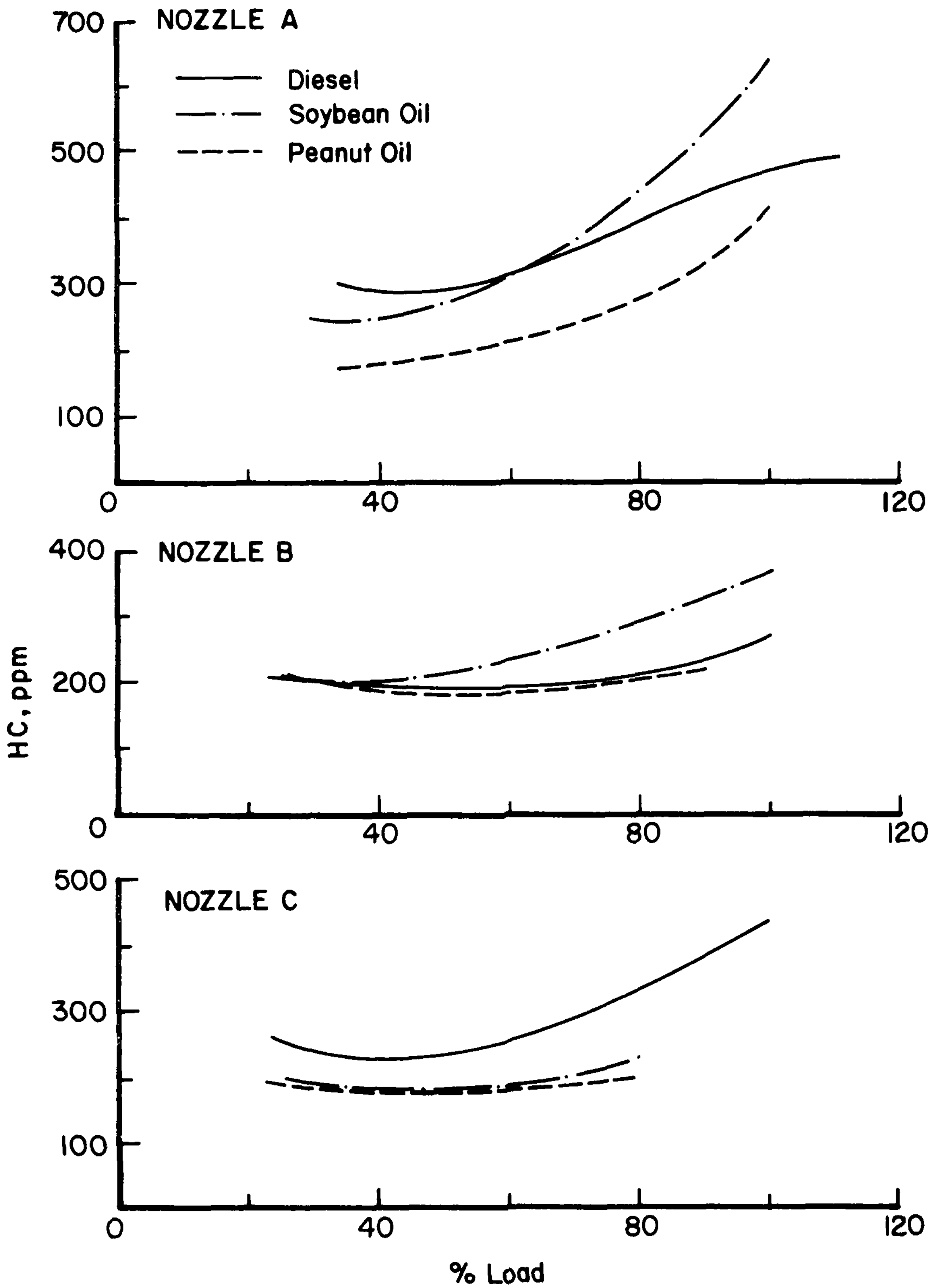


Figure 26. Variation of hydrocarbon emission for different fuels. (Source: R. Forgiel and K. S. Varde,"Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternative Fuels for Diesel Engines SP-503 [Warrendale, PA: SAE, 1981], p 61.)

Smoke tests revealed a slight increase in opacity for the 20-80 blend. Figure 27 shows an average reading of 0.5 units over baseline diesel values on the Bosch Smoke scale.[45] This increase is assumed to be caused by changes in injector spray atomization that accompanied the higher viscosity of the blend. This trend is also suggested by the higher smoke levels at lower temperatures.

Although many uncontrollable factors influenced the engine's fuel economy, mean results for consumption of straight diesel fuel and the 20-80 blend were approximately the same. Calculations for straight diesel averaged .584 L/km (4.03 mi/gal) and those for the 20-80 blend averaged .581 L/km (4.05 mi/gal). This agreement in mileage is most surprising in light of the different drivers, traffic, loading, and other variables.

After testing, the engine was disassembled and inspected. A carbon buildup of 1.6 mm (1/16 in.) was discovered on the engine head, piston heads, and injector tips. This accumulation was not considered excessive, considering the long idling times in the daily runs. Symmetrical firing patterns on the piston heads indicated adequate fuel passage through injector tip holes. Subsequent analysis of the injectors verified tolerable fuel hold time and pressure. Cylinders, rings, and intake ports checked out in good condition with no carbon or gum deposits.

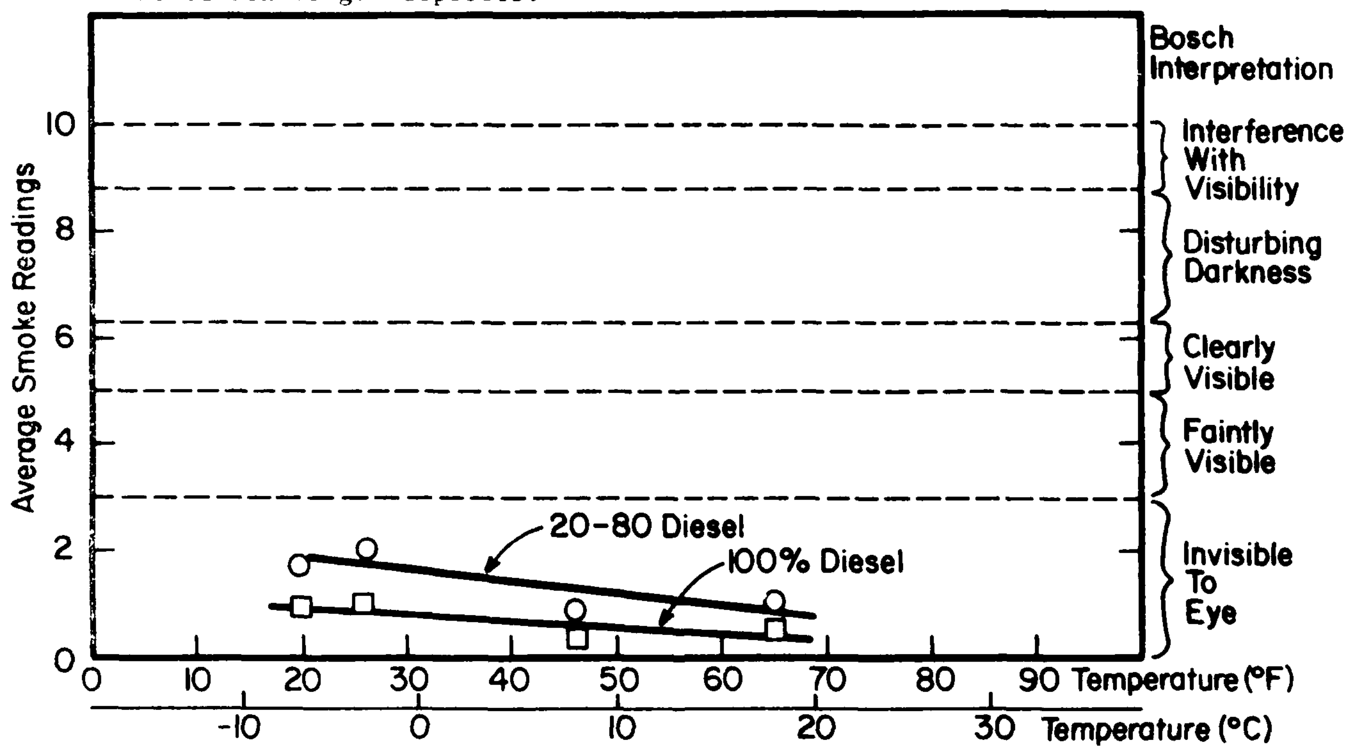


Figure 27. Effect of temperature on smoke output. (Source: M. K. Fishinger, et al., "Service Trials of Waste Vegetable Oil as a Diesel Fuel Supplement," Alternate Fuels for Diesel Engines SP 503 [Warrendale, PA: SAE, 1981], p 72.)

[45]Cardis Fishinger, et al., p 72.

The fuel blend solidified at -6.6°C (20°F). Waxing was so extensive in the fuel filter that flow was completely blocked. Past remedies for similar problems with No. 2 diesel have included fuel heaters and additives, but in this instance, a wax solvent high in toluene cleared the blockage.

Aside from clouding in cold weather, the vegetable oil/diesel fuel blend performed admirably. Satisfactory fuel efficiency, smoke emissions, and maintenance requirements were realized without engine modification. Noxious exhaust components were not monitored, however, and should be considered before large-scale use of this fuel. Also, no information was gathered on engine knock and limiting amounts of diesel substitution with vegetable oils.

Goering, et al., investigated the combustion of hybrid blends of vegetable oil and alcohol in a diesel engine.[46] They prepared thermodynamically stable microemulsions of aqueous ethanol and soybean oil to be used for testing. The soybean oil was chosen because of its abundance and low cost; ethanol was chosen as a nonpetroleum organic solvent to reduce the oil's viscosity. Blends were developed and compared with SAE specifications for No. 2 diesel fuel, with results listed in Tables 16 and 17.[47] Both ionic and nonionic emulsions were tested in an engine with the following specifications: three-cylinder, naturally aspirated diesel with 2491 L (147.6 cu in.) displacement and rated at 26.3 kW (35.27 hp) at 2400 rpm. In addition, No. 2 diesel fuel was burned for baseline values.

Short-term performance tests showed promising results in terms of power output, thermal efficiency, and knock (Table 18).[48] Power output of the hybrid fuels came within 5 percent of the baseline fuel. The nonionic blend almost reproduced the peak power of the No. 2 diesel, despite a 6 percent decrease in injection energy. This additional power per unit energy was achieved with an increase in BTE. The hybrid fuels sustained leaner combustion (smaller equivalence ratio) because of their oxygen content (Figure 28).[49] Although the hybrids' CN of 25 was substantially lower than the SAE recommendation of 40, the audible diesel knock with the baseline fuel did not increase with the hybrid blends.

Shortcomings of the hybrid fuels included increased BSFC and poor startability. Higher fueling rates and thus increased BSFC were due to the greater viscosity and lower heating values of the hybrids over the baseline fuel. Difficulty with engine startups necessitated the use of No. 2 diesel or ether, which were problem-free remedies.

---

[46] C. E. Goering, R. M. Campion, A. W. Schwab, and E. H. Pryde, "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, Proceedings of the International Conference on Plant and Vegetable Oils as Fuels, Fargo, ND, 2-4 August 1982, ASAE Publ. 4-82 (ASAE, 1982), pp 279-286.
[47] C. E. Goering, et al.
[48] C. E. Goering, et al.
[49] C. E. Goering, et al.

Table 16

Composition of the Hybrid Fuels

Fuel	Chemical	Fuel	
Soybean oil	--	52.3	53.3
190-Proof ethanol	C_2H_6O	17.4	13.3
1-Butanol	$C_4H_{10}O$	20.5	33.4
Linoleic acid	$C_{18}H_{32}O_2$	6.54	0
Triethyl amine	$C_6H_{15}N$	3.27	0

Source: C. E. Goering, et al., "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, Proc. Int. Conf. on Plant and Vegetable Oils as Fuels, Fargo, ND, 2-4 August 1982, ASAE Publ. 4-82 (St. Joseph, MI: ASAE, 1982).

Table 17

Calculated Properties of Fuels

	Fuel		
Property	Ionic Hybrid	Nonionic Hybrid	No. 2 Diesel
Higher heating value (kJ/kg)	36687	37045	45343*
Stoichiometric A/F ratio	11.60	11.57	14.55

*Measured.

Source: C. E. Goering, et al., "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, Proc. Int. Conf. on Plant and Vegetable Oils as Fuels, Fargo, ND, 2-4 August 1982, ASAE Publ. 4-82 (St. Joseph, MI: ASAE, 1982).

Table 18

Engine Performance at Maximum Power

Test Fuel	Max Power (kW)	Fuel Supplied (mg/injection)	Energy Supplied (kJ/injection)	Brake Thermal Efficiency (%)
No. 2 diesel	24.1	86.1	3.91	30.5
Ionic hybrid	22.9	101.2	3.71	32.2
Nonionic hybrid	23.7	99.9	3.70	32.3
No. 2 diesel	23.9	86.9	3.94	30.3

Source: C. E. Goering, et al., "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, Proc. Int. Conf. on Plant and Vegetable Oils as Fuels, Fargo, ND, 2-4 August 1982, ASAE Publ. 4-82 (St. Joseph, MI: ASAE, 1982).

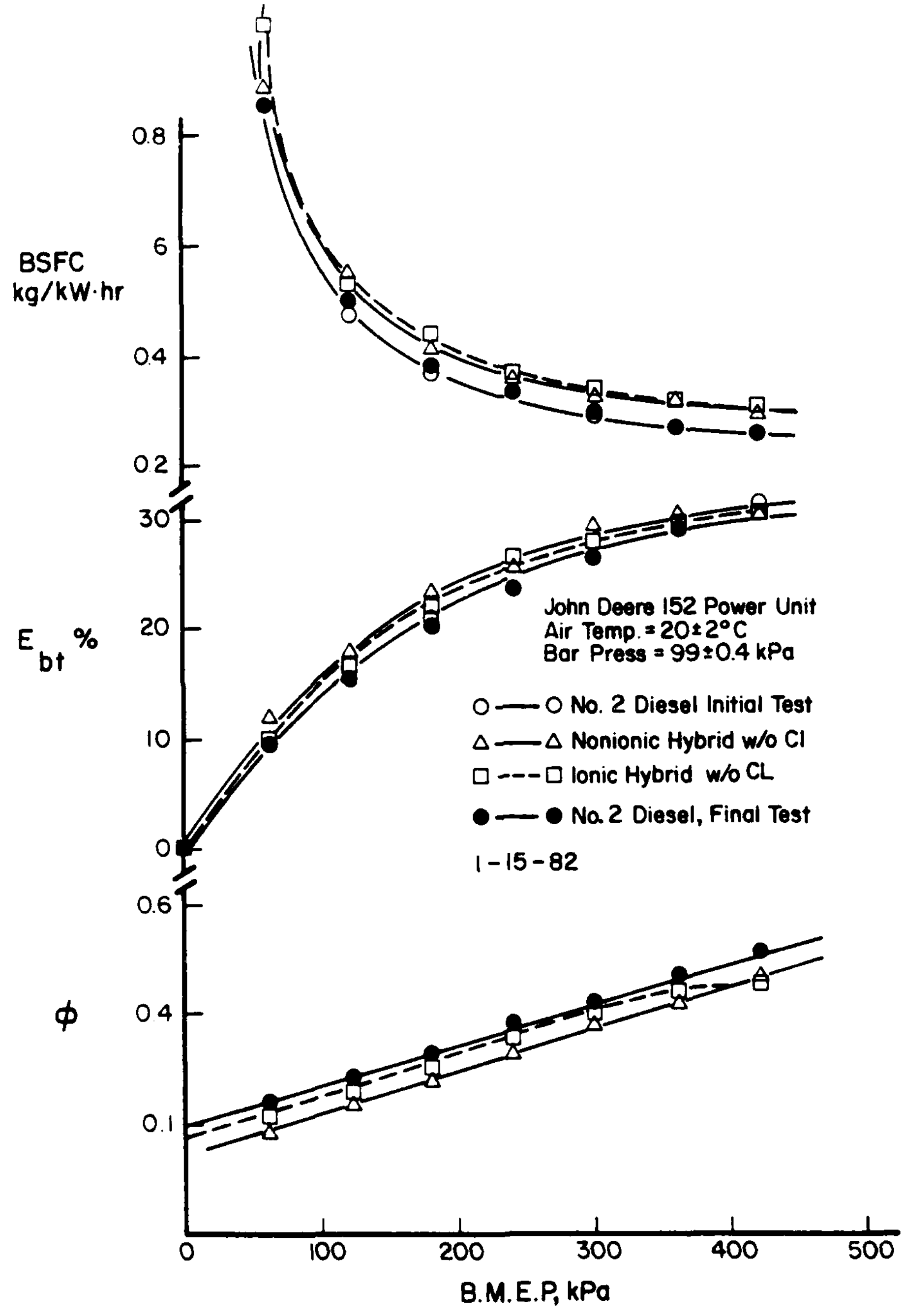


Figure 28. Diesel engine performance on diesel and hybrid fuels. (Source: C. E. Goering, et al., "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, ASAE Publ. 4-82 [St. Joseph, MI: ASAE, 1981].)

Effects of the hybrids on engine wear and emissions were not examined but possible safety and cost deterrents were mentioned. The hybrid fuels have a flash point between 22 and 28°C (72 and 82.9°F), which is low, but the fuels could be handled with methods suitable for straight ethanol with a flashpoint at 14.4°C (58.2°F). The hybrids' prohibitive costs were a concern, costing about 200 to 225 percent of the price of No. 2 diesel at the time of the study.

Vegetable oils tested included undiluted oils and blends with diesel fuel and alcohols. Undiluted soybean and peanut oil performed very well. Soybean oil produced the same power output as diesel fuel with similar BTE and knock and fewer emissions. Peanut oil could produce only 90 percent of baseline power output, but its efficiency equaled or surpassed diesel values; moreover, smoke emissions, nitrous oxides, and hydrocarbons were generally less than for diesel fuel. Peanut oil combustion did not increase noise production over diesel levels. Although these fuels' performance was excellent during warm-run, steady-state conditions, startup, cold, and long running conditions may present a problem. Startability with neat vegetable oils was not monitored, but other experiments have suggested that starting may be difficult. Hence, present systems may need to be retrofitted for a diesel or ether-assisted start. In addition, vegetable oils' high solidification temperatures may prevent cold-weather runs, and engine deposits may obstruct long-term operation.

The vegetable oil/diesel blend was the only fuel reviewed in a long-term field experiment, and results were encouraging. Apparently, normal operation was achieved in terms of power output and fuel economy in nearly 5000 miles. No retrofitting was done, but no knock or engine wear problems were reported. Smoke was the only emission monitored; only a slight increase in exhaust smoke opacity was detected.

The soy oil/ethanol blend performance was also acceptable, with engine noise no more intense than standard diesel knock. Power output was within 5 percent of the diesel level and thermal efficiency was comparable. On the negative side, faster fueling rates led to a BSFC greater than diesel's, and initial startup required a diesel or ether assist. Information on emissions and engine wear was not reported; also, the low flash point of this blend was noted as a possible safety hazard.

Table 8 summarizes experimental results from the vegetable oil fuels.

REFERENCES

Cheremisinoff, N. P. Gasohol for Energy Production (Ann Arbor Science, 1979).

Corps of Engineers Energy Program, Engineer Regulation 11-1-10 (Department of the Army, 15 April 1982).

Dunlay, J. B., et al., Economic and Technological Assessment of Diesel Engines Using Coal-Based Fuels for Electric Power Generation, NTIS TE4234-37-80 (U.S. Department of Energy, September 1979).

Dunlay, J. B., et al., Performance Tests of a Slow Speed, Two-Stroke Diesel Engine Using Coal-Based Fuels, NTIS TE7905-267-80, Contract No. EF-77-C-01-2647 (U.S. Department of Energy, June 1980).

Fishinger, M. K., et al., "Service Trial of Waste Vegetable Oil as a Diesel Fuel Supplement," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: Society of Automotive Engineers [SAE], October 1981).

Forgiel, R. and K. S. Varde, "Experimental Investigation of Vegetable Oils Utilization in a Direct Injection Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: SAE, 1981), pp 59-66.

Goering, C. E., R. M. Campion, A. W. Schawb, and E. H. Pryde, "Evaluation of Soyoil-Ethanol Microemulsions for Diesel Engines," Vegetable Oil Fuels, Proceedings of the International Conference on Plant and Vegetable Oils as Fuels, Fargo, ND, 2-4 August 1982, ASAE Publ. 4-82 (American Society of Agricultural Engineers [ASAE], 1982), pp 279-286.

Goering, C. E., et al., "Fuel Properties of Eleven Vegetable Oils," Transactions of the American Society of Agricultural Engineers (ASAE), Vol 25, No. 6 (1982), p 1473.

Gross, W. B., Cetane Rating Log Sheets from Workshop Engine Div. of Dressler Industries, Waukesha, WI (1980).

Hardenberg, H. O., and E. R. Ehnert, "Ignition Quality Determination Problems with Alternate Fuels for Compression Ignition Engines," Alternate Fuels for Diesel Engines SP-503 (Warrendale, PA: SAE, 1981), pp 51-57.

Heisey, J. B., and S. S. Lestz, "Aqueous Alcohol Fumigation of a Single-Cylinder DI Diesel Engine," Alternate Fuels for Diesel Engines SP-503 (Tulsa, OK: SAE, 1981), pp 1-14.

Krawetz, C. A., Test Report No. 01215 2-4 from Phoenix Chemical Lab., Inc., Chicago, IL (1980).

Marshal, H. P., et al., "Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel Slurries," Alternate Fuels SP-480 (SAE, 1981), pp 59-70.

Miller, C. L., and J. L. Smith, "Using Butanol Fuel Blends," ASAE paper 80-15 24, presented at ASAE Winter Meeting, 2-5 December 1980 (St. Joseph, MI: ASAE, 1980).

Obert, E. F., The Internal Combustion Engine and Air Pollution, 3rd ed. (Harper and Row, 1973).

Schaefer, A. J., and H. O. Hardenberg, "Ignition Improvers for Ethanol Fuels," Alternate Fuels SP-480 (Warrendale, PA: SAE, 1981), pp 9-20.

Shirvani, H., Alternate Fuels for Diesel Engines, unpublished master's thesis (University of Illinois, 1982), p 25.

Shirvani, H., C. E. Goering, and S. C. Sorenson, Performance of Alcohol Blends in Diesel Engines, SAE Paper 810681 (Warrendale, PA: SAE, 1981).

CERL DISTRIBUTION

Chief of Engineers
ATTN: Tech Monitor
ATTN: DAEN-ASI-L (2)
ATTN: DAEN-CCP
ATTN: DAEN-CW
ATTN: DAEN-CWE
ATTN: DAEN-CWM-R
ATTN: DAEN-CWO
ATTN: DAEN-CWP
ATTN: DAEN-[illegible]
ATTN: DAEN-[illegible]
ATTN: DAEN-[illegible]
ATTN: DAEN-ECE
ATTN: DAEN-ZCR
ATTN: DAEN-RD
ATTN: DAEN-RDC
ATTN: DAEN-RDM
ATTN: DAEN-RM
ATTN: DAEN-ZCZ
ATTN: DAEN-ZCE
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM

FESA, ATTN: Library 22060
ATTN: [illegible]

US Army Engineer Districts
ATTN: Library (41)

US Army Engineer Divisions
ATTN: Library (14)

US Army Europe
AEAEN-ODCS/Engr 09403
ISAE 09081
V Corps
ATTN: DEH (11)
VII Corps
ATTN: DEH (15)
21st Support Command
ATTN: DEH (12)
USA Berlin
ATTN: DEH (11)
USASETAF
ATTN: DEH (10)
Allied Command Europe (ACE)
ATTN: DEH (3)

8th USA, Korea (19)

ROK/US Combined Forces Command 96301
ATTN: EUSA-HHC-CFC/Engr

USA Japan (USARJ)
ATTN: AJEN-FE 96343
ATTN: DEH-Honshu 96343
ATTN: DEH-Okinawa 96331

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

416th Engineer Command 60623
ATTN: Facilities Engineer

US Military Academy 10966
ATTN: Facilities Engineer
ATTN: Dept of Geography & Computer Science
ATTN: DSCPER/MAEN-A

AMMRC, ATTN: DRXMR-WE 02172

USA ARRCOM 61299
ATTN: DRCIS-RI-I
ATTN: DRSAR-IS

DARCOM - Dir., Inst., & Svcs.
ATTN: DEH (23)

DLA ATTN: DLA-WI 22314

DNA ATTN: NADS 20305

FORSCOM
FORSCOM Engineer, ATTN: AFEN-DEH
ATTN: DEH (23)

HSC
ATTN: HSLO-F 78234
ATTN: Facilities Engineer
Fitzsimons AMC 80240
Walter Reed AMC 20012

INSCOM - Ch, Instl. Div.
ATTN: Facilities Engineer (3)

MDW
ATTN: DEH (3)

MTMC
ATTN: MTMC-SA 20315
ATTN: Facilities Engineer (3)

NARADCOM, ATTN: DRDNA-F [illegible]

TARCOM, Fac. Div. 48090

TRADOC
HQ, TRADOC, ATTN: ATEN-DEH
ATTN: DEH (19)

TSARCOM, ATTN: STSAS-F 63120

USACC
ATTN: Facilities Engineer (2)

WESTCOM
ATTN: DEH
Fort Shafter 96858
ATTN: APEN-IM

SHAPE 09055
ATTN: Survivability Section, CCB-OPS
Infrastructure Branch, LANDA

HQ USEUCOM 09128
ATTN: ECJ 4/7-LOE

Fort Belvoir, VA 22060 (7)
ATTN: Canadian Liaison Officer
ATTN: Water Resources Support Center
ATTN: Engr Studies Center
ATTN: Engr Topographic Lab
ATTN: ATZA-DTE-SU
ATTN: ATZA-DTE-EM
ATTN: R&D Command

CRREL, ATTN: Library 03755

WES, ATTN: Library 39180

HQ, XVIII Airborne Corps and
Ft. Bragg 28307
ATTN: AFZA-FE-EE

Chanute AFB, IL 61868
3345 CES/DE, Stop 27

Norton AFB CA 92409
ATTN: AFRCE-MX/DEE

Tyndall AFB, FL 32403
AFESC/Engineering & Service Lab

NAFAC
ATTN: RDT&E Liaison Office (6)
ATTN: Sr. Tech. FAC-03T 22332
ATTN: Asst. CDR R&D, FAC-03 22332

NCEL 93041
ATTN: Library (Code L08A)

Defense Technical Info. Center 22314
ATTN: DDA (12)

Engineering Societies Library
New York, NY 10017

National Guard Bureau 20310
Installation Division

US Government Printing Office 22304
Receiving Section/Depository Copies (2)

US Army Env. Hygiene Agency
ATTN: HSHB-E 21010

National Bureau of Standards 20760

Army Fuels and Lubricants Laboratory
Fort Belvoir, VA [illegible]

[illegible]

Sliwinski, Ben J.
Diesel fuel alternatives for medium-speed engines in civil works prime movers / by B. J. Sliwinski, E. Corcoran. – Champaign, Ill : Construction Engineering Research Laboratory ; available from NTIS, 1984.
69 pp. (Interim report / Construction Engineering Research Laboratory ; E-200)

1. Diesel fuels. I. Corcoran, E. II. Title. III. Series: Interim report (Construction Engineering Research Laboratory) ; E-200.